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Volume 2 2016

Including lecture articles from the AGM 2015, the Newcastle Symposium 2015, OUGS Members' field trip reports, the Annual Report for 2015, and the 2015 Moyra Eldridge Photographic Competition winning and highly commended photographs

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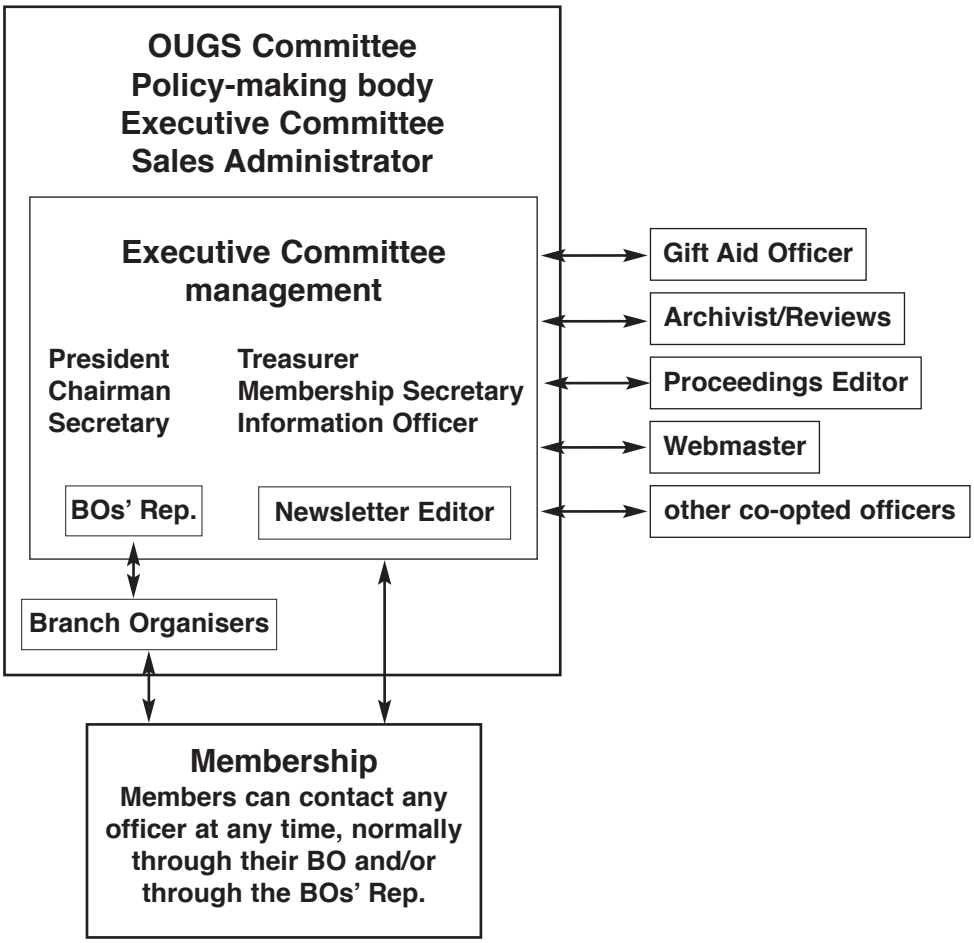


Editorial:

Dear readers,

I would like to begin this editorial by thanking all members who filled out the OUGS Executive Committee's most recent survey, and for the many kind comments people made about our publication in its new guise as the Proceedings of the OUGS. *One of you even commented, "Zealot high quality product"! I've never quite thought of myself as, "a person who is zealous, especially to an extreme or excessive degree; a fanatic," but I do strive to give you a decent publication.*

This issue comprises articles from the speakers at our Annual General Meeting weekend in April 2015 and at our Symposium in July 2015 in Newcastle upon Tyne, entitled, 'Pangaea: Life and Times on a Super Continent: a celebration of Britain's unique marine Permian strata'.

First we are given a new perspective on the great Permo-Triassic mass extinction, new thoughts about recovery after mass extinction and new discoveries from Chinese fossil sites, by Prof. Mike Benton of Bristol University, who has delivered lectures to us many times at OUGS weekends.

Our Geoff Brown Memorial Lecture for 2015 was given by Prof. Kathy Cashman, also of Bristol University, on the ever fascinating research on volcanic eruptions and their effects on society.

Our Symposium in Newcastle has produced a host of articles ranging from a detailed and informative summary of Pangaea and the Permian geology of north-east England by Dr Paul Williams, to a summing up of the lectures by our President, Dr Tom Argles. In between are articles on recent research and interpretations of the North Pennines Orefield, on Zechstein carbonates and the Permian Rotliegend sandstones, and on the mining of Zechstein evaporites.

Then you can read a sweeping history of geological research through more than a century on the Permian in north-east England, followed by two final articles demonstrating the increasing engagement of geologists and the public. The Limestone Landscapes Project and outreach programmes in geoconservation and geodiversity are two examples of how the public, both UK and foreign visitors, are becoming more engaged with there landscapes and local building traditions.

There follow four field trip reports at home and abroad. And interestingly, thinking of the increasing engagement of the public with geology and geography just alluded to, on our final field day of Tom Argles's Presidential Field Trip, 'Mantle in the Mountains' to Andalucía, Spain, we 'met' hundreds of seemingly eager Spaniards from very young to quite elderly out on the Nigüelas Fault east of Granada enjoying Spain's national 'Geolodía' (Geology Day)! There follow several further field trip reports, including one from the Newcastle Symposium, and another field excursion to a Welsh locality by the seemingly indefatigable John Downes.

Also included is a short report on a field trip dedicated to visiting the final resting place of the 'Father of English Geology' William Smith, and a useful article on a crystallography and mineralogy workshop/study weekend hosted last year by the Severnside Branch.

Articles in this issue finish with an unusual twist and twill in a report by Michael Perkins of the East of Scotland Branch on a visit to see the Great Tapestry of Scotland. Michael picks out the geological elements woven into the tapestry and describes them to us with colourful (fabriculous!) photographs intertwined with his text.

One of the privileges and perils of editorship of a society publication and an 'Editorial' blank page is that you may, within reason, 'say things about people'. Theoretically speaking, a final offering in this issue is a salutory note from Diana Smith, former OUGS Chairman and OUGS Tutor (to which I would add the epithet 'extraordinaire!'). Incidentally, Diana, for better or worse, is hugely responsible for my becoming OUGS Newsletter *Editor earlier this century, and now your* Proceedings *(formerly* Journal*) Editor.*

Diana attended a GS London meeting last June on 'Higher Education network and University Geosciences in the UK' and wrote a précis of each speaker's address. The message is interesting and informative, and it comes not only from UK shores, but is an international one. It is the opinion of this editor that we should definitely heed Diana's final advice.

Last, but certainly not least, I want to express my gratitude to all those who help me produce this publication for you. Thank you to all you worthy transcribers who toil through our AGM and Symposium lecture recordings to provide transcriptions for the speakers to help them in writing up their articles for us to publish: Philip Clark, Maggie Deytrikh, Averil Leaver, Dick Millard, Sally Munnings, Isabel O'Brien, Jenny Parry and Norma Rothwell.

Thank you also to Linda Fowler, Don Cameron and Sue Vernon for your continued support and advice and proofreading. A special thank you to Sue Hughes who has become our proofreader (assuming the experience hasn't put her off!). And thank you to Professor Jose Benavente and to Dr Carlos Sanz de Galdeano of the University of Granada for their welcome at the Nigüelas Fault, Andalucía, and for providing the photographs for the figures on pages 113 and 114.

Finally, I'd like to explain the charming little vignettes that you will find next to the titles of the articles beginning on pages 33, 39, 55 and 63. These are character sketches by our very own Thalia, drawn as she listened to the lectures at the Newcastle Symposium. Linda McArdell and I were able to persuade Thalia to let us use them, and to which the authors readily agreed as well. (And just for the record, in Greek mythology Thalia [Θάλεια] is one of the Three Graces, the Muse for comedy and idyllic poetry, and a Nereid [a sea nymph]!)

As always, I wish you happy reading.

— David M. Jones, OUGS Proceedings Editor

OUGS AGM 2015 Keynote Lecture

Evolutionary recovery after mass extinctions

Mike Benton

(University of Bristol)

[OUGS AGM 2015; original transcription by Sandy Colville-Stewart and Helen Coombs from the symposium recording; edited by Prof. Benton and POUGS Editor David M. Jones.]

Introduction

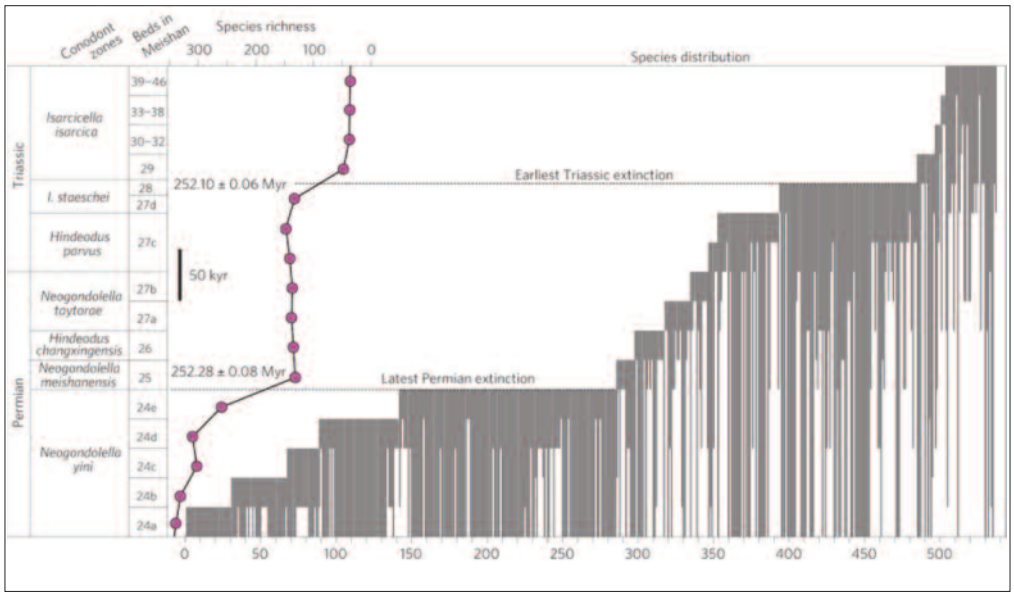
I want to talk about recovery rather than about the extinction event itself, other than in the briefest terms. I'm interested here in talking about recovery because of course we often focus on mass extinctions only in negative terms, and yet, clearly, life survived and life came back, and in fact this particular event, as was the case with many of the others, punctuated the trajectory of life and probably had an important influence on life as we see it today.

This is a rough outline of what I want to talk about:

- a little bit about China, where I've had the great privilege and pleasure to do field work over a number of years now, and
- a little bit about methods and ways that palaeontologists can try to extract evolutionary information from the fossil occurrences

If you read about the Permo-Triassic mass extinction you may see a diagram like this (Fig. 1). This is a classic kind of range chart and you've all seen them I know. The detail doesn't matter, but this is well documented in China because the quality of stratigraphy is very good across the boundary. Not only are there good fossil occurrences that allow them to divide up the succession into many, many zones, they believe that it's very complete, that there's not a lot of time missing, and it is very fossil rich; and as well as the paleontological evidence there are volcanic ash beds, from which we can get a number of radiometric dates through the sequence.

Figure 1 A typical diuagram of Permo-Triassic mass extinction.



The extinction event and sites

So, in this diagram you are looking at more than 500 species of invertebrates; they're plotted in sequence according to the times of their extinctions, so it is a sort of step-wise pattern of extinctions. The stratigraphy is based mainly on conodonts and the Permo–Triassic boundary is here [*pointing*]; and the two extinction levels bracket that boundary. And people debate back and forwards about whether there is there a single level of extinction or two levels? It's the sort of semantic question, whether you wish to call Level B a separate extinction event, but for the moment we'll just do that. What's been argued from this evidence is that numerous species come and go through time, as you would expect, and then at Level A 90% of species disappear at that one level. Then there is an episode up to Level B of rather strange evolution, which I'll say something about in a moment, and then at Level B there appears to be another extinction where something like 80% or 90% of species disappear. Various versions of this diagram have been published — this is the latest one from *Nature Geoscience* in 2013.

Now, what's this episode between A and B? First of all, because of radiometric dating, and now the quality of the dating, we are able to say that the spacing is something like 180,000 years. So there are exact radiometric age dates here, here, and then at different points up and down because of these ash beds; so 180,000 years, that's the level of precision that we wouldn't have expected a number of years ago; and the other curious thing to notice is that something changes between Levels A and B: there are lots of steps of extinction, but almost all of the species going extinct are very short lived. So up to Level A there is a sort of random selection of long-lived and short-lived species, and then that pattern returns again in the Triassic after Level B; but in that space in between the steps of extinction are mainly very short-lived species so that they originate and go extinct within an increment of that stratigraphic column — and these are typically what people would call disaster species. They struggle into existence, they do what they do, they quickly go extinct and something else comes along and they're a sort of quick turn-over. And another point is, for the moment at least, that we seem to be calling this the Permo–Triassic extinction rather than the end-Permian extinction because the first level, A, was before the end of the Permian if you're being very exact, and if you

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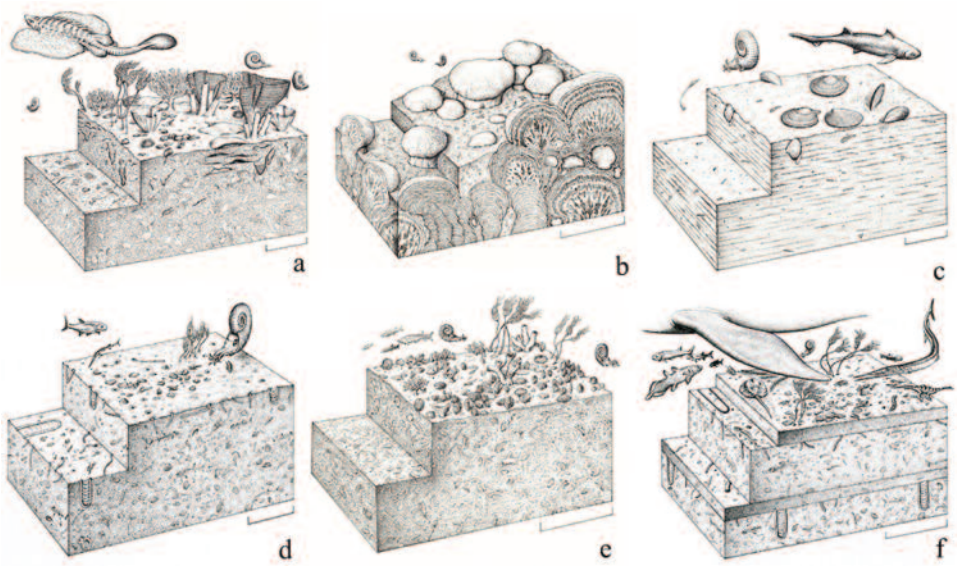


Figure 2 Permo-Triassic environmental change.

regard Level B as another part of the extinction that's already into the Triassic.

The other fact to be aware of is that physical conditions on the Earth apparently did not return to normal for five or six millions years after the P–T boundary, and so some of you will be familiar with this diagram (Fig. 2). It's a very famous summary of carbon isotopic values through the Permo–Triassic boundary, all the way through the early Triassic and into the middle Triassic. These data are from work by Jonathan Payne published in *Science* in 2004, and what he found was that not only was there the well-known carbon spike or excursion at the P–T boundary, but also, importantly, that this was repeated several times, maybe three more times at different points during the early Triassic. When that was first published people thought, oh well, maybe this isn't quite right but a great deal of effort has gone into measuring and comparing other sections and so this seems to be real and then you can see that once you're into the middle Triassic it kind of settles down at a fairly steady level. Those sorts of perturbations, each of these peaks, represents a time of flash heating, global warming on a dramatic scale. So in terms of the recovery, we need to be aware of the fact that conditions on the Earth didn't just return to normal immediately.

Some of you may know that the global strata of type for the Permo–Triassic boundary is indeed in China, in Meishan. It's worth a visit if you enjoy visiting geoparks — this is a real geopark in the sense that they've made a kind of park and funfair out of it. It's not at all popular but the effort that's gone into it is fantastic, with a huge car park, cafeterias and stuff that you'd expect; and there's a 'sensuround' cinema of four dimensional experience in which you can actually walk up the steps and the boundary is labelled, so they point you right at it. There's no doubt and everybody's encouraged to visit … but there we are, they do things properly. Around the corner you can see why perhaps it was chosen, as it's a very complete succession: great volumes of marine sediments enable you to track through the uppermost Permian continuously into the Triassic, so that it's been possible to collect centimetre by centimetre, as you can see, to do those stable-isotope measurements, document fossil occurrences and all the other sorts of evidence that help you to try to understand what's going on. It's not only close to the boundary, which is well documented, but in fact the marine sections in south China continue right up through the Triassic into the late Triassic. [Pointed out on his slide] So Meishan is over here near Nanjing, and Shanghai is somewhere in there; there's Hong Kong and Yunnan Province, I'll show you some pictures from there; and Beijing is up here, so all across South China this great basin — something like 2,000km wide — all of it, or almost all of it, marine Triassic. When I started my interest in this [extinction event] a number of years ago, the thought of visiting these places was just impossible. Now it is easy — anybody can go. The point of this diagram, and again the details don't matter, is that not only do you have good documentation of the transition at Meishan, but there are also many other sections that give you the rest of that succession; so several kilometres of continuous sedimentation can be documented.

Luoping, Xingyi and Guanling

We've spent some time in different locations, but one location that took me there and why I was first invited is this site of Luoping, which is in Yunnan Province. Here a team of geologists in China found exceptionally preserved fossils and with the help of students and farmers they effectively dug away half a hill (Fig. 3, *opposite*). What you are looking at is a hill that has just been dug away and they were able to step up through the whole succession collecting tons of rock and fossils at each level. And the reason that they were excited about this Luoping site, or set of sites really, is the exceptional marine, shallow marine, fauna of mainly the vertebrates, which I suppose attracted their attention. There are ichthyosaurs, some other isolated marine reptiles, and there are many fish, including *Saurichthys*, a common well-known middle Triassic fish something like a pike, a predatory fish, plus lots of other heavily-scaled fishes; there are also arthropods, *Limulus*; there are lobsters; and rather well-preserved sea-urchins with all their spines in place. There are also terrestrial things that got washed in, bits of plants, insects, teeth of dinosaurs or dinosaur-like creatures, a millipede — all sorts of odd and strange creatures — and so in the collection, just over a summer, they collected 20,000 identifiable, exceptional fossils from the site.

Working with our Chinese colleagues, and with a wonderful Australian artist named Brian Choo, we were able to 'reconstruct' this ancient world. Brian did these fantastic reconstructions of a series of marine Triassic fossil lagerstätten — they call them exceptional biotas in China — with lots of fish, ichthyosaurs, a placodont, a lobster here fighting placodonts, and all sorts of other wonderful creatures (Fig. 4, *page 4*).

At a slightly younger site — that's Middle Anisian, Ladinian — Xingyi is another lägerstatte particularly well-known for the sauropterygians, the nothosaurs and the pachypleurosaurs, as well as for the placodonts; and there are ichthyosaurs, lots of ammonites, fish and other things there as well.

Guanling is probably the most famous of these lagerstätten from Triassic China, and is particularly known for the giant crinoids. Some of you may be familiar with these creatures from the

Figure 3 The Luoping fossil site in Yunnan Province.

Posidonienschiefer of Germany, but Guanling has just the same, where you can see them fossilised and lying flat-out on the marine sediments, logs with these enormous long crinoids, maybe four or five metres long trailing behind some kind of plankton sieving, pseudo-planktonic system; and living among these would be all kinds of fish and marine reptiles and other vertebrates.

So it's no wonder that these sites have led to a lot of excitement and this is one of the many sets of lagerstätten that are producing wonderful fossils in China at the moment. Obviously they are rather over-written or less-famous than the Jehol biotas of early Cretaceous age with feathered dinosaurs, but these have attracted a lot of attention too.

Recovery of life

We were interested in aspects of the recovery of life, and you can see this in a very simple way if you compare a succession of earliest Triassic, next level up, next level up — and as you get into the Triassic you can see the way the ecosystem is kind of building. The important point to note is that in these marine successions a lot of the fishes were inherited from the Permian, so many of those continue, as do many of the invertebrates, but in very different proportions. You all know, of course, that the Permo–Triassic mass extinction dealt the death knell to trilobites, and to rugose and tabulate corals; and that various other groups entirely disappeared, and then that those ecological roles had to be recovered slowly and eventually by other groups of corals and the crustaceans such as lobsters and shrimps. As these animals rose to prominence in the Triassic, obviously the brachiopods never recovered; and bivalves and various other groups took over. But wholly new are the marine reptiles. There is not a hint of these marine reptile groups in the Permian and yet they emerge, certainly by the Olenekian — maybe some were even in the Induan — in the early Triassic, certainly by the end of the early Triassic. So within three or four million years of the extinction we already have the first representatives of these several different groups of marine reptiles; and by the time of Luoping in the middle Triassic they've diversified further and you have the shell-crushing placodonts and even large ichthyosaurs and thalattosaurs, some types of which are getting to be many metres in length. By the late Triassic ichthyosaurs reached gigantic size, the biggest marine reptiles ever; and some of the shonisaurs and shastasaurs were maybe seven or eight metres in length. So they're more whale-like in size than anything else.

In attempting to document the recovery the first approach of course is simply understanding the succession: which groups appear, when do they appear and that kind of thing. One thing becomes rather evident when you do that simple stratigraphic approach: that the first phase of the recovery was a very difficult time and most of the evidence suggests rather rapid recovery — somewhat debated, but I think the debate is rather semantic because of course certain groups like ammonoids and conodonts recovered quickly in Induan in the beginning of the Triassic but they were hit again by these repeated isotopic excursions, which represent repeated, dramatic environmental change. So in a classic 'spindle' diagram *[as in Jonathan Payne's work, mentioned above — Ed.]* we can almost separate this block of time across the Permo–Triassic boundary. You can see the extinction of various groups at that point in these marine and terrestrial environments, lots of groups entirely wiped out, some just surviving and recovering, but during this time of six million years of rapid isotopic fluctuation there are certain groups that did *not* recover.

It's very easy to remember: the coal gap, the coral gap, the chert gap — three Cs. In deep seas there were no cherts being formed, the siliceous organisms that would have formed those cherts in a normal-functioning ocean just weren't there and so cherts are not accumulating. Secondly, no coral reefs because, of course, the corals have been killed off, or at least if any survived they were minor, hidden parts of the ecosystems. Corals only came back rather later, the modern scleractinian corals.

On land there was the coal gap. Of course that's an observation of the distribution of sedimentary rocks, but it's an implication that there just weren't any trees around — and maybe that that was part of the extinction.

More ways of looking at recovery

Let's look at other ways of trying to understand the recovery. This is important because you then can see very probable links between the physical environment as documented by the sediments and the isotopes, delaying recovery and impacting on the nature of the evolutionary process, but also that it is dependant on documenting occurrences of fossils as point occurrences, where we can do it, to look at the fossils in a phylogenetic context, an evolutionary context. With colleagues in China we're pushing this approach forward — this is the beginning if you like, and we

Figure 4 A reconstruction of a marine Triassic fossil lagerstätten, or 'exceptional biota' by Australian artist Brian Choo, based on the Luoping fossil site in Yunnan Province, China.

have quite a way to go in trying to adopt these approaches, but this is what we've been able to do here.

I want to take you, maybe for some of you, further from your comfort zone in later parts of the lecture by talking about macro-evolution; how we can use an improved stratigraphic time-scale and a thorough and careful documentation of the fossils to try to calculate certain aspects of evolution from that information. Not least are things like rates of change — that's a relatively straight-forward thing. Here, macro-evolution is just evolution above the species level.

What are the different components we need? One of these is the phylogenetic tree. Phylogenetic trees are a very important aspect of much of what I am going to talk about. You're all familiar with these, you may be aware that the production of ever bigger trees is feasible these days and can be done using a variety of different methods and a variety of different sources of information, and some of you will have seen some that are absolutely huge. They may be for modern organisms compiled from genomic data, from DNA, or in our cases we're going to be doing it from the fossils; in some cases you can do a combined effort.

I'll try not to go too far with this idea, just enough to introduce some of the concepts. When you're talking about evolution in a mathematical sense you're looking for patterns, and the simplest way to find patterns, in a statistical sense, is to demonstrate something that diverges from random, something that cannot be explained by a random process. Statisticians use two terms in this case: they will often say that the random pattern is either a random walk or sometimes they use this term 'Brownian Motion'. You'll be familiar with both of these. In an earlier version things moved, all these little particles jumped about, so Brownian Motion is that classical image of atoms bouncing around and moving in an apparently kind of random way.

There are different kinds of patterns of evolution, and may be a little easier to follow where time is, as usual, on the y-axis and a character or a trait on the x-axis, and so the random model of evolution, Brownian Motion, is shown by this kind of tree where splitting is just happening more or less equally to left and right. In contrast, in the trend case there is more splitting happening in this direction so the whole population, the whole group, is heading off in that particular direction.

The final method or terminology I just want to remind you of is the distinction between diversity and disparity. Normally, palaeontologists will use the word diversity simply to mean number of species, or number of families, or number of genera; whereas disparity is the *morphological* diversity — but just to avoid that possible confusion of use of the word 'diversity' we tend to call it 'disparity'. So disparity, then, is the amount of difference in terms of morphological difference, forgetting the taxonomy. Putting these two together, how do diversity and disparity change through time? This is where we get to the surprising discovery. The null expectation would be that the two are coupled, meaning that as diversity increases disparity increases at the same rate; and if you prefer to look at this as a tree here it is (Fig. 5); it's just a normal Brownian Motion kind of tree that's expanding at a kind of regular rate in time and as the species split the range of morphology keeps increasing; and if you prefer to plot it with amount of change on the x-axis and time on the y-axis, disparity and diversity more or less increase in parallel, so that's implying they are coupled and that makes sense, that would be the sort of basic commonsense expectation: that as the species split they get ever more different.

The other two possibilities are that diversity and disparity are decoupled, meaning that each follows its own course — that they are not connected exactly. You could have a pattern of diversity first, where speciation rate is the same but the amount of morphology is quite limited, and so disparity is increasing very slowly, whereas diversity is increasing at the same rate — so here we have the diversity rising and the disparity coming rather later. Or, you could have this kind of early burst type of model where it's disparity first, so morphology expands fast and then speciation fills up that amount of space through the same span of time. In all these three trees at the top the rate of species-splitting is the same in each case. If we can identify which of these is the commonest pattern in nature, we might be discovering something important about how evolution works and entirely from fossil data.

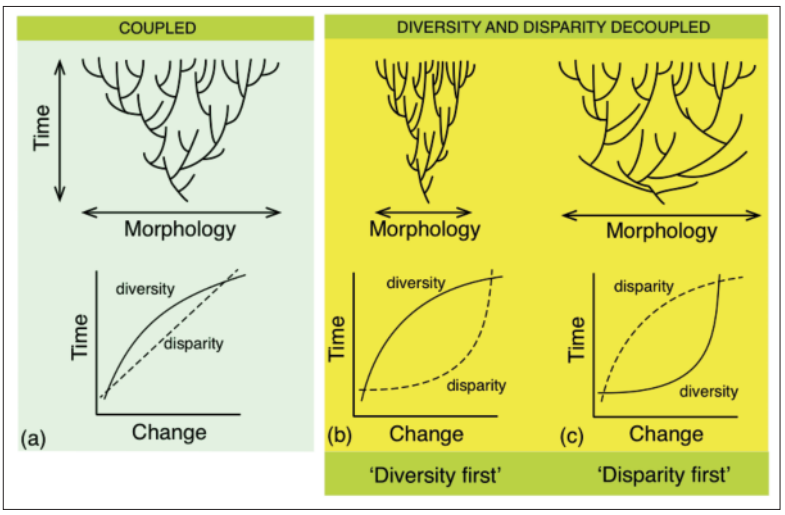
This is nothing to do with any of the modern areas of biology that normally would be used — making use of genomics as a way of getting at the process of evolution; there are other patterns as well. I can tell you, first of all, that this is the dominant pattern from the fossil record; however you measure the disparity, it doesn't matter, that's how it is, predominantly, in the fossil record, and that's telling us something quite extraordinary — it's telling us that we don't really see much difference in post-extinction times and normal times because often people have thought 'you clear the world, you empty the world of life, and in this post-extinction world somehow the normal rules of evolution will run awry' and that evolution would then run very fast because there's so much opportunity, there's so little competition.

Maybe that's true, but we don't really see any difference from groups that radiate in other times. If you compare the pattern of expansion of birds, the normal assumption is that the early evolution of birds was not triggered by a preceding mass extinction, that you have *Archaeopteryx*, you then have all these amazing birds from the Cretaceous of China. That sort of explosion of early birds was in no way, I don't think, triggered by any preceding mass extinction; whereas in the Triassic, which we are going to look at in a bit more detail, clearly was and yet you still seem to get the same pattern, so far — and that's based now on hundreds of studies where people have tried to look at many different groups in many different ways — so morphology first then diversity.

Macro-evolution

That gives a very clear steer of how we should understand one of the most fascinating parts of macro-evolution, that is, the adaptive radiation. Think back to G. G. Simpson in 1944 *[Tempo and Mode in Evolution, Columbia UP — Ed.]*, when he presented a diagrammatic way to marry palaeontology and modern biology and gave a model of adaptive radiation that fits this kind of explanation. It seems that, for whatever reason — whether it's the

Figure 5 Diversity and disparity 'decouled'.



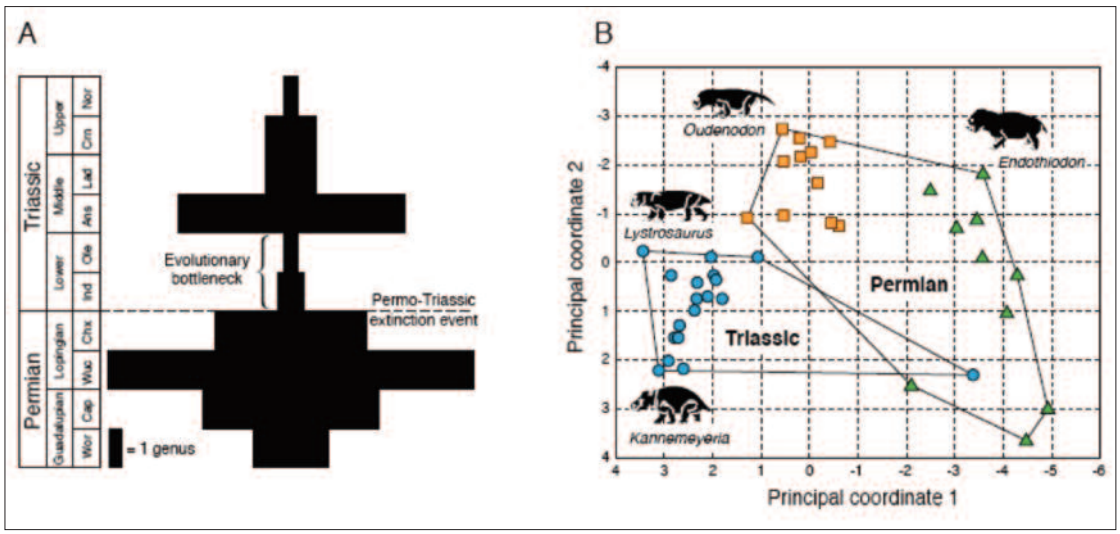


Figure 6 (A) A classic 'spindle' diagram of species fluctuation through time. (B) Lystrosaurus *range chart through Triassic and Permian times, compiled by Jörg Fröbisch.*

opportunity after a mass extinction, or the opportunity of a new character — whatever it is that makes birds successful, the group will then explode, it will do everything that is possible, to the limits, and then after that the group is successful, it fills up the space.

Let's have a look at a couple of case studies of groups that recovered in the Triassic and see what they show. Here is a nice example of what could be called 'an evolutionary bottleneck' — the dicynodonts. They were very important herbivores on land at the end of the Permian, then they were nearly wiped out. I think three or four species survived, including, famously, *Lystrosaurus*, and then for a span of time — indeed this particular time of environmental awkwardness or ghastliness — they didn't recover much at all. And then they kind of explosively radiated in the Middle Triassic and eventually tailed off and disappeared in the Late Triassic. This is a spindle diagram (Fig. 6A), meant to represent the number of species, more or less; and at one time that would have been all you could have done, and said, 'Oh right that's interesting'; and that's it. But now you can go a lot further, and I'll show you how we were able to try to marry together a study of the diversity, but also the disparity, to try to understand what was going on.

Lystrosaurus is a famous fossil for all sorts of reasons. The diversity data are quite rich, this is a range chart compiled by Jörg Fröbisch a number of years ago (Fig. 6B) and these are very common fossils — they were bulky creatures, and so were easily fossilised; they're well known from the Karoo in Southern Africa, from the Permo–Triassic red beds of Russia, from China, and from various other parts of the world.

In terms of the phylogeny, there is the Permo–Triassic boundary here; and here are all the Late Permian forms, those Middle Triassic forms, and the survivors: one, two, three, four. So this is *Lystrosaurus*, this is *Myosaurus* and these two we don't know, but these are leading up to these particular groups here, so we don't have any fossils here, but we know that there must have been precursors of those surviving across the boundary. So four, only two of which actually led to the explosion of diversity; and these two — *Lystrosaurus* and *Myosaurus* — they are examples of what has come to be known as 'dead clade walking'. They are organisms that survived but they shouldn't really have because they don't lead to anything at all, and it is important just to keep that in mind briefly.

So what we then tried to do was to measure the range of morphology of all these dicynodonts through the Permo–Triassic boundary. And it kind of confirmed what we thought we might find. First of all let me explain: this diagram is a geometrical representation of all of the different aspects of morphology that we were able to measure, summarised and simplified into a simple x/y plot. It is a very standard sort of output from a variety of kinds multi-variant statistical summaries, examples of which I am sure you will have seen these in many different contexts. You can read them in a very exact geometric way in terms of the area occupied, so you can say for these Permian forms, these are maybe Middle Permian, these are maybe Late Permian — so you can actually plot and see where they sit, and the points that are closest are the most physically similar, while those that are farthest apart are — in terms of morphology — the most different. And then you can look at the areas occupied through time — so in the late Permian they occupy a large area of this morphospace, in the Triassic shown in blue they occupy a rather smaller area; and we were a bit honest when we published this because we included over here *Myosaurus*, but remember that it was a 'dead clade walking', and we should have removed it for that reason. The Middle Triassic forms are just over here, so the effect of the bottleneck was, again, that disparity and diversity are decoupled, and although diversity recovered more or less to something like the pre-extinction level, morphology never did.

So this is evidence of a complex effect of the extinction event and that something in the survivors is very different. The event had massively reduced their adaptive possibilities, or something like that.

The rise of dinosaurs

My third and final example is the origin of dinosaurs, which until recently I wouldn't have linked, most people wouldn't have linked, with the Permo–Triassic mass extinction. But in a way now perhaps we can. Normally, you may recall, we would understand that the dinosaurs originated in the Late Triassic — the oldest dinosaurs are typically from South America, the Ischigualasto Formation of Argentina for example — and the oldest body fossils occur *c.* 230Mya; and here is the Permo–Triassic mass extinction. However, in the last five or six years quite a lot of evidence has been found that pulls the origin of dinosaurs from the Late Triassic down into the end of the Early Triassic. So, at first that was quite a hard thing to swallow, that was quite difficult to accept; and certainly the first inkling of this came from fossil tracks. Of course tracks are always something you have got to be a little bit careful about because people will hypothesise from tracks, but it is often not absolutely defensible. I am sure many of you will know examples. However, soon after these tracks dinosaur-like from Poland were announced, also other fossils

came from the Middle Triassic of Tanzania; and although the Tanzanian examples were not dinosaurs, they were the nearest relatives of dinosaurs — in terms of the evolutionary tree, the sister group, the nearest relatives. If you've got them down here in the Middle Triassic, dinosaurs must have come down there as well because they shared a common ancestor and you can only have one common ancestor.

[Here a 'gratuitous picture of early dinosaurs' was shown 'just to cheer you up a bit' — Ed.] Here are some of the early dinosaurs: this is *Coelophysis* and these are Late Triassic, of course, so we don't know exactly what these very first dinosaurs looked like. Even if they originated at that time, they were not abundant, they were not common, so we've not quite been able to track them back yet in detail.

Well, we've used these numerical methods to try to understand a little bit more about the macroevolution of the origin of the dinosaurs. When I came into the business many years ago the common assumption was that, the common argument was, that life was so knocked sideways by the extinction event that the various groups that were around in the Early and Middle Triassic were kind of struggling to survive — and there may be some truth in that, I don't know. It did actually connect the origin of dinosaurs to the Permo–Triassic mass extinction.

But nonetheless, eventually the dinosaurs succeeded by brute force. It was very much a kind of competitive scenario, and the argument was that the dinosaurs were warm-blooded, or they had big sharp teeth, or they stood upright and could run fast, or a variety of other explanations were given for why they were better, why they survived.

So a number of years ago we did one of the first of these kinds of studies, where the student Steven Brusatte (now on the staff at U Edinburgh), a very active young American, tried to find a way to explore how the first dinosaurs may or may not have interacted with their supposed competitors. And so this is where we did the first effort to try to establish disparity, and the relative amounts of morphospace they were occupying.

So for the Late Triassic, first of all in this cartoon (Fig. 7), we have the dinosaurs shown in this sort of green colour and we have their supposed competitors — the Crurotarans, which are things like phytosaurs, ornithosuchids and rauisuchids, and all these strange toothy creatures that I showed you a moment ago. These were still the biggest creatures, the top predators. They were feeding on these earliest dinosaurs. And the previous idea then would have been that when the dinosaurs came on the scene they would have taken over and they would have had a negative effect on their competitors.

So there is the disparity where Crurotarsans were dominant and we get into the early Jurassic and by this point a lot of Crurotarsans have gone extinct and we only have the precursors of crocodiles left, and yet the dinosaurs are still more or less just pottering, they are not doing much, they are just sitting there in the same area of morphospace more or less, and it looks as if they are not actually even responding to the extinction of their supposed competitors.

Then, comparing change in disparity through time — through the Middle Triassic, through the Late Triassic into the Jurassic — the amount of disparity of Crurotarsans was rising and then plummeted because, of course, across the boundary they went down to very little; while for the dinosaurs (shown in this greenish colour) disparity rises and rises and then sort of levels across the boundary. We haven't taken this research further forward, but the disparity probably then picks up and rises again.

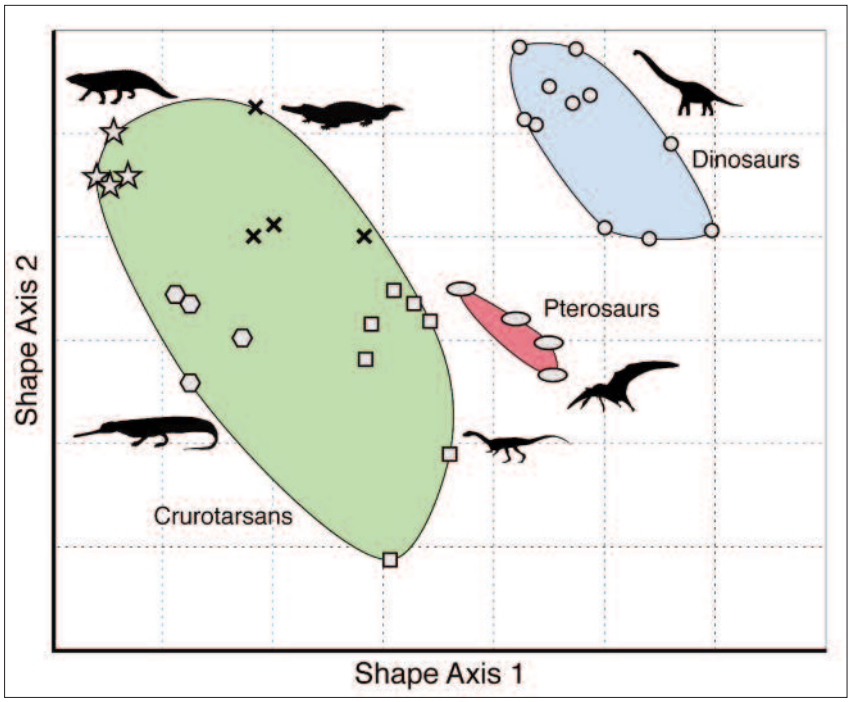
The conclusion from this analysis, it's a slightly different aspect than the decoupling, was that we couldn't really see evidence that the dinosaurs as a whole were somehow having a negative impact on the Crurotarsans as a whole, and the extinction of the Crurotarsans at the end of the Triassic was due to that mass extinction event, which probably or possibly followed a similar model to the end-curve in involving global warming, acid rain, ocean stagnation and all those sorts of things. So this was an attempt to try to read more into the kinds of macro-ecological interactions that people would have talked about.

Some concluding remarks

I can't show you finished results for these ideas about evolutionary diversity and disparity, but the above are a few illustrations of certain approaches that can be used, showing that there are many ways of describing 'recovery'; and I think there is an increasing interest in it. The Triassic recovery is one of the most fascinating now, because of the Chinese deposits, it can be really well documented in a way that maybe 10 or 20 years ago people would have said was impossible, that our knowledge is too limited. In Europe for example you can't really do this because the Permo–Triassic boundary in, for example, Germany is mainly within terrestrial red beds and then switches in the Middle Triassic to marine and then in the Late Triassic switches back to terrestrial; and in Britain it is as complex or more complex, so regrettably in much of Europe, and similarly in North America, it is actually very difficult to get a good continuous succession.

So, there are different aspects, and diversity through time is obviously one approach — succession, which I described earlier, at the beginning and up to a certain point, was about the limit of

Figure 7 Cartoon of Late Triassic dinosaurs and their supposed competitors, the Crurotarans.



what palaeontologists would have done; or they might have talked about major clades, brachiopods declining, bivalves increasing, that kind of thing. Gills, for example, were seen as a way of trying to identify the diets and modes of life of different groups — and it can be done not considering taxonomy at all, just trying to document different types of predators; and of course through this time the range of gills changed. That may be linked to ecological structure, the sort of food-web reconstruction approach.

I've talked, then, about disparity. I've been a little bit vague about how we collect the data, but there are several different types of data that we can use in these plots. I have to say, our students now are very bright — they quickly learn all this stuff and collect vast amounts of data. They seem to be very well able to understand and do these calculations so that you can use the cladistic data sets, which is what we have done, as a quick, easy way to get a lot of data without doing a lot of measurements. Morphometric would be measuring aspects of the structure, including lengths with ratios or indeed landmark measurements — some of you may be familiar with the idea of landmarks, where you have photographs of a trilobite or a skull or something, and dot your way round it in exact spots and then you can compare shapes. In dong this one of the most interesting is the idea of functional disparity, that is, trying to document aspects of feeding or locomotion in repeatable ways so you can actually try to determine whether the range of diets has increased or decreased — that sort of thing.

I have really not talked about the phylogenetic methods and diversification shifts other than to introduce you to the idea of random walks, but there are ways that we've not yet applied in these examples too. For example, take an evolutionary tree, take a simple measurement of body size and then do calculations of the ancestral states and that enables you to track back to the bottom of the tree. Then you can calculate rates of change through time, and the hope is to find points at which they go beyond the expectations of a random walk — then they increase at a more rapid rate, for example.

One plot that we did, just a very quick rough effort for the Chinese vertebrates, tracking, the numbers of feeding gills of fishes in blue, and remains fairly constant through the Triassic. But feeding gills of reptiles, they increase rather dramatically from the Early Triassic, then in the Middle Triassic plummet and rise again. So these are wholly new feeding styles of these marine reptiles and they get bigger through time, so again this is the roughly Triassic timescale against the Chinese biotas and these are the small ones, the medium ones and the large ones. That's a progression in size change through time, a very simple demonstration.

So to summarize, I think I have shown you some different approach, starting with the familiar kind of field work but then maybe just open it out a bit to show how you can use those raw data to try to read a lot more than you might have thought you could get out of the fossils. I think there's a very important research area here. It is enabled by improvements in the methods, because now there are methods available that were not available 10 or so years ago; but at the same time, improvements in our knowledge of the fossil record, of course, and, very importantly, improvements in the time scale. We all know that the quality of time scales is crucial, particularly because of improvements in radiometric dating; and indeed so is simple access to the localities that we couldn't get at before. That's very important because if you are going to do any study of evolution you have to have a good-quality time scale, of course.

Making large phylogenetic trees has become a sort of game — people who churn them out; they want to make ever bigger and more complex trees, and it becomes a sort of object of pride that you can wrestle a result out of a massive data set. Good for them. We can then use them because once they've cracked it you've got a very valuable research tool to use.

All of these new numerical techniques are really transforming the field. All of the young palaeontologists in Bristol are learning this stuff, I'm teaching it to our third years. For those who did [OU course] S364 there was a very strong component about clades from Peter Skelton and Peter Sheldon. They were on to it, it has now been around for a while, but there are now these improved methods that make it even easier to do.

I also think it is interesting, as a final point, to remind ourselves that the role of palaeontology in understanding evolution, in understanding biology, and that this role has often been quite subservient — palaeontologists are an apologetic lot and so we are always saying, "Yes, I am sorry the fossil record isn't very good, it is very incomplete." We are always beating our breasts about the inadequacies of the data, which is correct of course — one mustn't pretend things are what they are not — but if these two points are true then here are two examples (and there are many more that you can think of I am sure) of discoveries about evolution that we didn't know a few years ago and that I don't think you could get at without the kind of quality data methods that I have described.

So if this is true that in all groups — plants, animals, planktonic organisms, dinosaurs, everything pretty much — then that is telling us something about a key aspect of evolution. For, obviously, even people who don't care about palaeontology at all will still ask a question like, "Why are birds so successful?" Think about it, there are 10,000 species of birds around us today and the sister group of birds is crocodiles (23 species). Crocodiles and birds have evolved in parallel since the Early Triassic. They split at that time, they have shared the Earth for that span of time, they have lived through the same climate changes, the same mass extinctions — 23 species vs 10,000 species. And the only difference then has to be to do with their novelties, their characters, their morphologies, their adaptability, and that's an example of why it matters to understand adaptive radiations, diversifications, whatever you want to call them. Therefore we collectively as palaeontologists over the last 20 or 30 years have been doing these calculations in different ways, and it doesn't matter where you get your morphological data from, you find you can say to yourself, 'disparity first and diversity second — interesting.

And secondly, although not yet been thoroughly demonstrated, but seemingly broadly true, is that the periods of recovery of life in times following mass extinctions don't actually seem to be special times. They are special in the sense that so many groups are radiating, of course — and in the case of the Triassic the times were special in terms of the continuing grim physical conditions (seriously perturbed oceans and atmospheres for five or six million years — kind of unexpected but seemingly confirmed).

Until recently, it has been commonplace to assume that these times after mass extinctions must have been unusual or strange; and that evolution must have sort of run wild. But we don't find any evidence of that, so this may be an important discovery.
Thank you very much.

OUGS AGM 2015 Geoff Brown Memorial Lecture

Volcanoes and human societies

Katharine V. Cashman

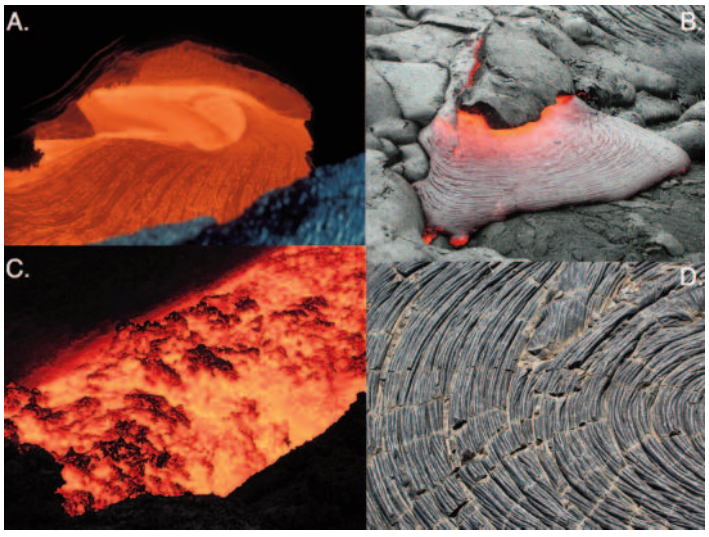
(School of Earth Sciences, University of Bristol)

Introduction

In many parts of the world humans live in the shadow of neighbouring volcanoes. It is estimated that around the world, *c.* 800 million people live within 100km of an active volcano (Fig. 1). This proximity has its benefits: Italian wines, Iceland's geothermal energy, Chile's copper deposits and many of Hawaii's rich oral traditions derive from the volcanoes that create these landscapes. Living close to volcanoes also presents problems that range from the nuisance caused by small and/or low-intensity eruptions to major disruption, or even mass migration, caused by large explosive eruptions. Here I explore the impact of volcanism on human societies, using examples from both the present and the past. My goals are first, to introduce a few of the most common volcanic hazards, and second, to explore the range of impacts generated by volcanic processes, particularly from the perspective of temporal (immediate vs long-lived) and spatial (local vs regional vs global) perspectives on volcano-human interactions.

One of the more benign forms of volcanic activity comprises effusive outpourings of lava. Most common are lava flows formed from basaltic magma (Fig. 2), generated as a consequence of melting the Earth's mantle. The simple phase diagram in Figure 3 shows two common causes of mantle melting. One way to melt the mantle is by heating, or increasing the temperature. Melting by heating is common in hot spot environments such as Hawaii. Figure 3 also shows, however, that decompression can cause melting. Decompression-driven melting supplies basaltic magma to the mid-ocean ridges, and therefore helps to create the oceanic crust that covers *c.* 70% of the Earth's surface. Basaltic lava flows in Iceland, which is located over a hot spot on a mid-ocean ridge, are created by a combination of melting by heating and melting by decompression.

Figure 2 Photographs of basaltic lava flows: (A) lava flowing through a lava tube in Hawaii; (B) Hawaiian pāhoehoe lava 'breaking out' from a thin solid crust; (C) a rough-surface 'ā'a flow from Mount Etna, Italy; (D) solidified pāhoehoe 'ropes' in Hawaii.



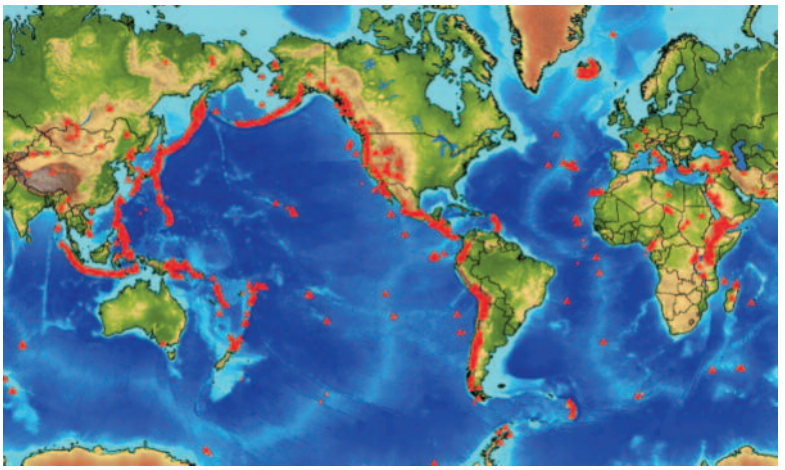
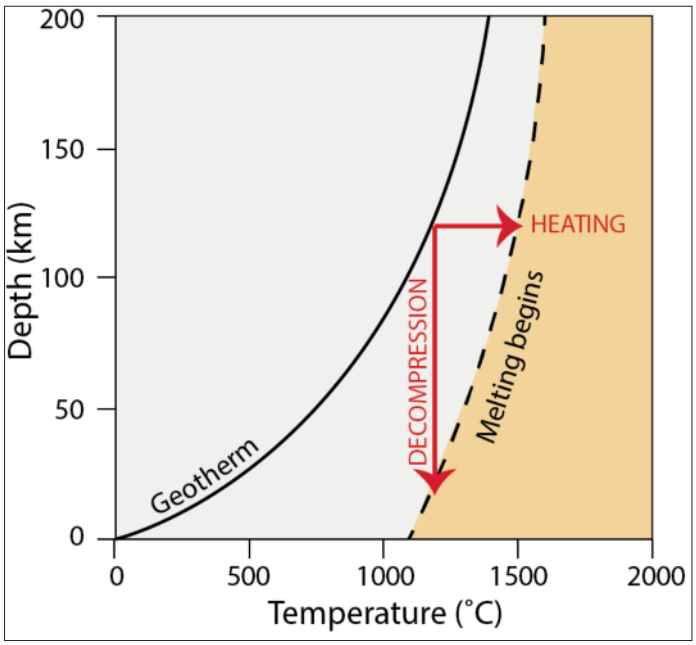


Figure 1 Volcanoes of the world (map originally sourced from the Global Volcanism Program, Smithsonian Institution. http://volcano.si.edu/).

A basaltic laboratory

Hawaii has long been used as a laboratory for studying basaltic lava flows, because here they are both frequent and commonly long-lived. In fact, the current eruption of Kilauea volcano started in 1983, and thus has lasted for more than 30 years. Since 1800, frequent lava flows have erupted from Kilauea and Mauna Loa volcanoes; in the early 19th century, the volcano Hualalai (near the tourist area Kailua-Kona) also showed lava

Figure 3 Two ways to melt the Earth's mantle, shown as a phase diagram, where grey is solid rock and orange is rock plus melt. The solid line labelled geotherm shows the normal increase in temperature with increasing depth (pressure) in the Earth. Within this simple framework, melting the mantle requires diverging from the geotherm either by heating at constant depth (pressure) or decompressing at constant temperature, or some combination of both.



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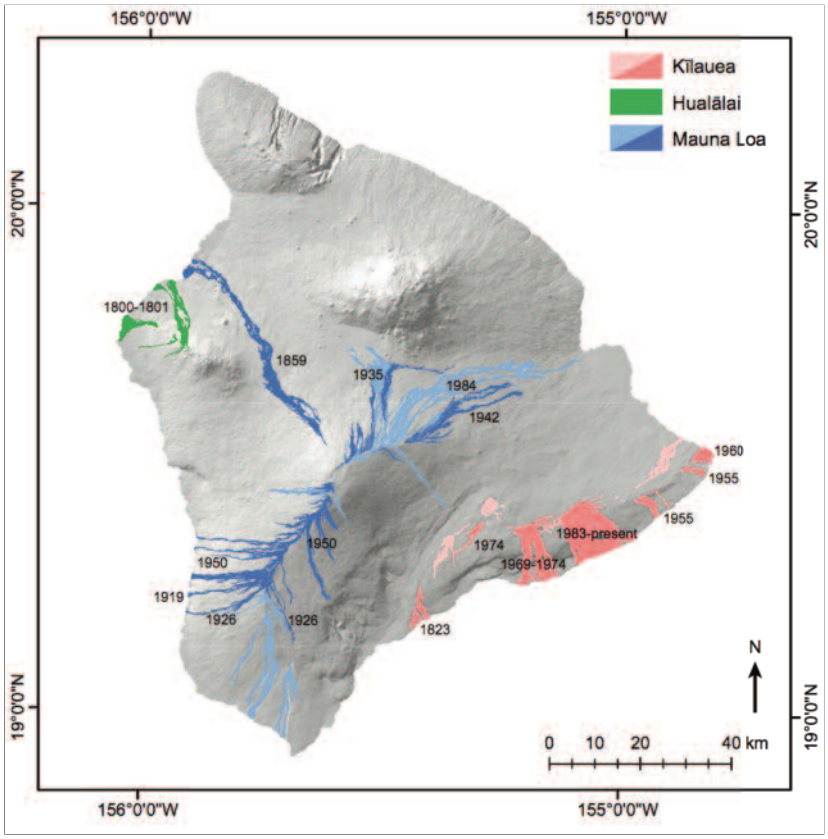


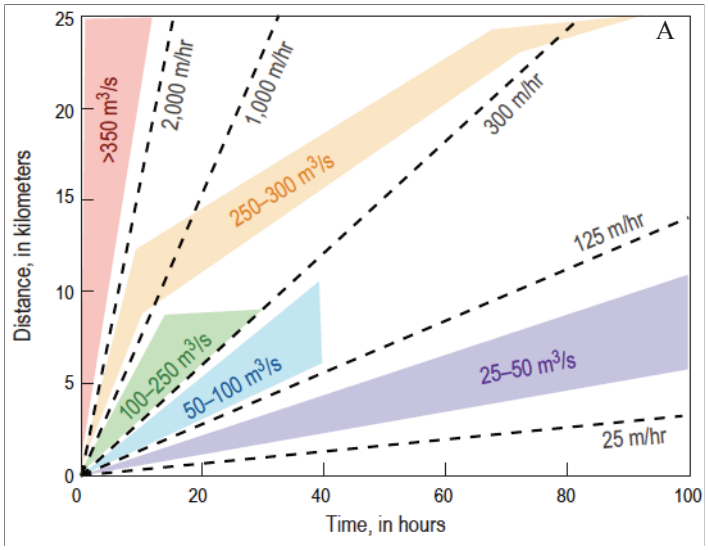
Figure 4 Historic (since AD 1800) lava flows from the three active volcanoes in Hawaii (denoted by colour). Flow dates are labeled (Cashman and Mangan 2014).

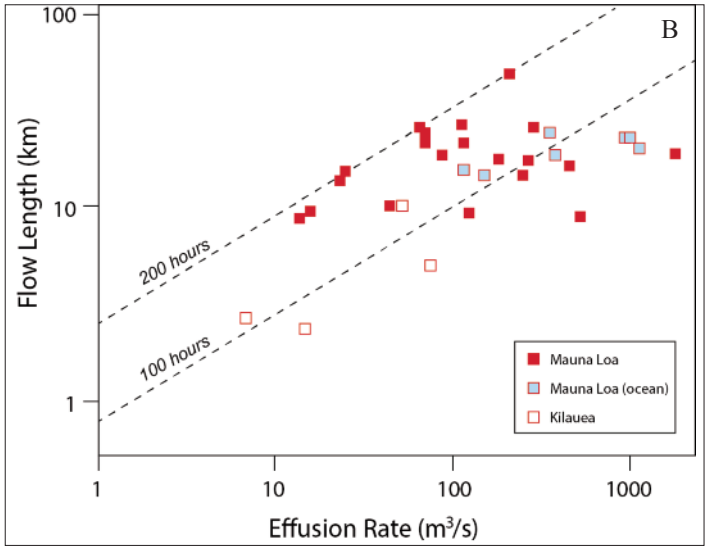
flow activity (Fig. 4). The long-term activity of Hawaiian volcanoes has required the local population to adapt to volcanic eruptions. One important step toward hazard mitigation has been the creation of the Hawaiian Volcanoes National Park, which contains much of the volcanic activity within its borders. Of course, volcanic activity does not recognise political boundaries, and thus there are times when lava flows approach human settlements. This occurred in 1993, when lava flows overran the small settlement of Kalapana on Kilauea's south-east coast, and most recently in late 2014/early 2015, when lava flows threatened the town of Pahoa on the eastern side of the island. At these times, volcanologists are asked to answer very specific questions, such as where the flows will go, and how far and fast they will travel. Answering these questions requires a detailed understanding of how lava moves across, and interacts with, the landscape.

One approach to studying lava flows is to see how they have behaved in the past. Figure 5 shows two compilations from Hawaii, one that examines the speed (velocity) of lava flows (dashed lines in Fig. 5A) and one that shows how far different lava flows have travelled (Fig. 5B). Note that both the flow velocity and the flow length (distance travelled) tend to increase with increases in the effusion rate, or mass eruption rate (MER). When viewed in detail, however, it is clear that lava flow length, in particular, can vary by an order of magnitude for the same MER. Thus these compilation plots provide broad guidelines for hazard assessment, but do not provide specific hazard information.

A clue to the variability of lava flow length comes from the outlines of individual lava flows. A simple example is shown in Figure 6 *(opposite)*. This figure shows a single lava flow erupted from Kilauea's Puu Oo vent in 1983. Note that this lava 'flow' actually comprises three separate flow lobes from the Puu Oo vent. Moreover, the longest flow lobe, which travelled first north-east and then north-north-east, splits to form two separate branches. The velocity of this flow was measured by tracking the location of the flow front(s) over time. Importantly, when the flow split, the advance rate of each of the two branches dropped to approximately half of the original advance rate (Fig. 6A). A compilation of data from several different individual Puu Oo lava flows shows this generally to be the case, as illustrated by the location of points along the 2:1 line, which shows that the advance rate before splitting was twice as fast as the advance rate after splitting (Fig. 6B). Exceptions represent flows that split as they crossed over the Hilina Pali fault scarp, where the abrupt slope increase caused them to speed up even as they split.

Figure 5 Lengths and advance rates of Hawaiian lava flows: (A) variations in distance as a function of time for recent lava flows — colours denote different effusion rates (labelled); plot is contoured to show average rates of flow advance in metres per hour; (B) variations in lava flow length as a function of effusion rate — note that most lava flows in Hawaii travel ≤ 25 km from the source, even when a wide range of average effusion rate is considered (modified from Cashman and Mangan 2014).





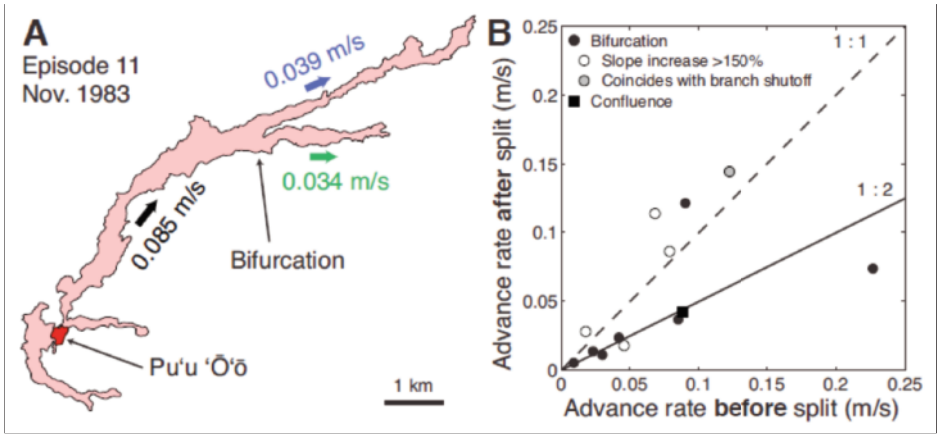


Figure 6 Effects of flow splitting on rates of Hawaiian lava flow advance: (A) example of a single flow erupted in November, 1983 — velocities of each main segment are labelled; note that after splitting, each flow lobe advances at a rate that is approximately half of the original advance rate; (B) comparison of advance rate before and after splitting, for several different lava flows erupted in 1983–1986; most fall along the 2:1 line (the flows advance at one half the original speed after splitting), except where the split flows travelled down steeper slopes (Dietterich and Cashman 2014).

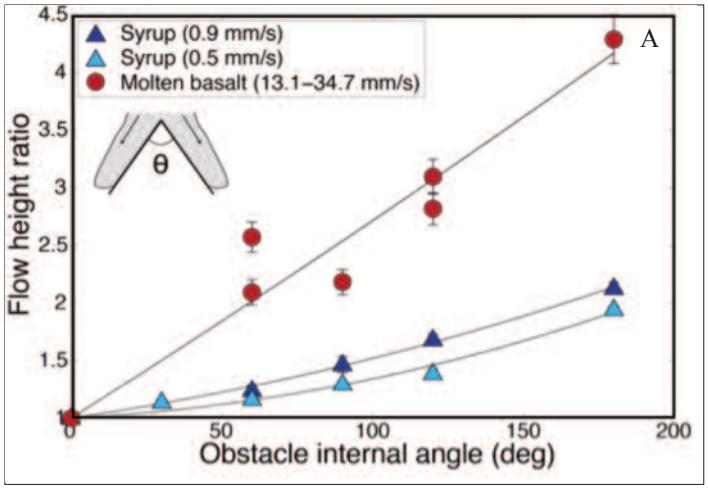
Experimental flows and flow barriers

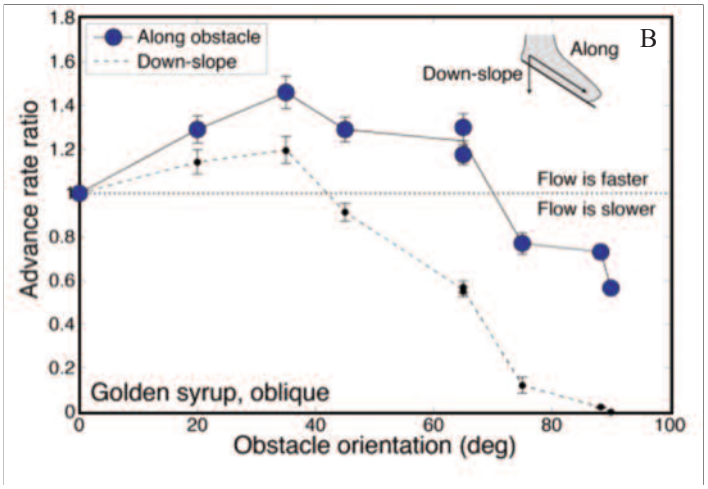
The lava flow shown in Figure 6 can be described as a distributary flow form; this is similar to branching rivers that form deltas, and contrasts with the typical tributary form of most rivers, where small streams feed into and build larger water flows. Why are lava flows distributary? The simple answer is that they are often fed from a single vent, or point source, and branch as they flow away from the source, most commonly because they interact with the pre-existing topography. To determine the ways in which topography affects lava flow advance, we have run a series of experiments in the laboratory. Most of the experiments involved the interaction of golden syrup — a simple analogue for viscous lava flows — with wedge-shaped obstacles having internal angles of 30˚ to 180˚. We also ran a limited set of experiments at the LAVA facility in Syracuse, NY (http://lavaproject.syr.edu/) using molten basalt and the same range of obstacle shapes (Fig. 7). Together these experiments confirm that flows slow after splitting (e.g., Fig. 6) and further show that (1) flows thicken upslope of obstacles by an amount that depends on both the obstacle angle and the flow speed (Fig. 8A), and (2) that flows encountering oblique obstacles may either speed up or slow down, depending on the obstacle angle (Fig. 8B).

These experiments are important for two reasons. First, they illustrate both the ways in which lava flows can interact with, and respond to, topographic roughness; this is important for developing the next generation of lava flow models. They also provide key insight into design of lava flow barriers (Table 1, *see page 16*). The earliest known attempt to control lava flows was during an eruption of Mt Etna volcano, Italy, in 1669, where citizens of Catania temporarily diverted lava into a neighboring village by breaching the (natural) levees that controlled the direction of flow. More recently, attempts to divert lava flows at both Kilauea and Etna have similarly attempted to redirect lava flows near their source by either breaching lateral levees or by constructing earthen barriers. The only successful

Figure 7 LAVA facility at Syracuse University, New York, USA (http://lavaproject.syr.edu/): (a) experimental set-up, with large furnace for melting lava and pouring slope; (b) example of an experimental flow diverted by an oblique barrier (photographs courtesy of Hannah Dietterich).

Figure 8 Results of experiments with obstacles: (A) flow height ratio (flow height just above obstacle compared with flow height without obstacle) for flows of golden syrup (blue triangles) and molten basalt (red circles); (B) intersection of golden syrup flows with an oblique obstacle. These data show that flows speed up along oblique obstacles oriented at high angles to the flow, but slow down when obstacles approach an orientation that is perpendicular to the flow (Dietterich et al. *2015).*





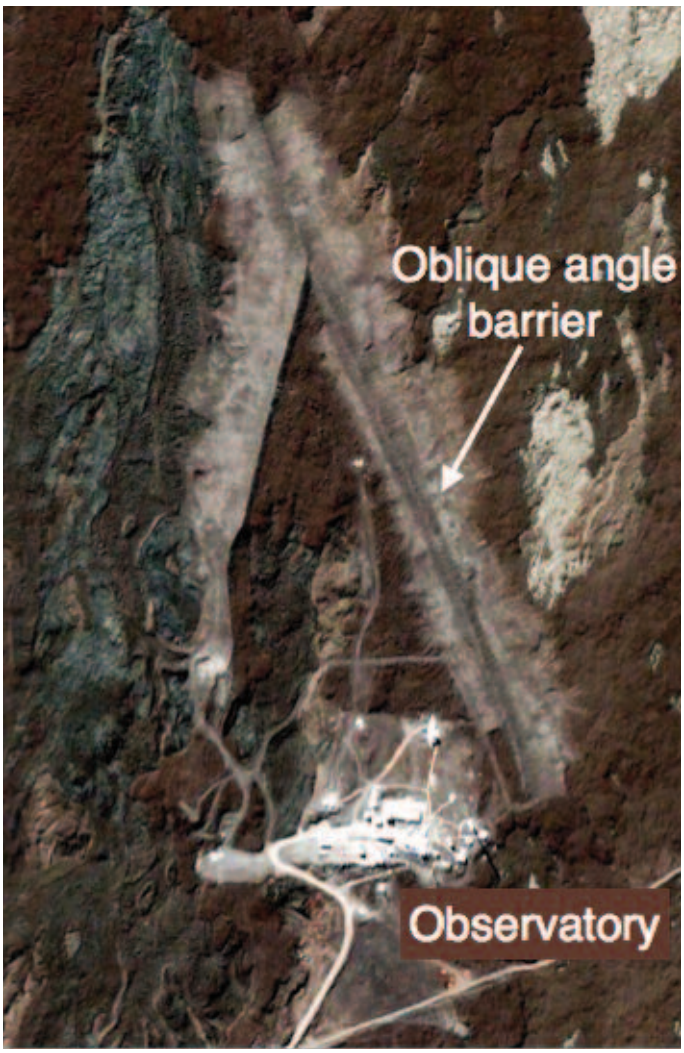


Figure 9 Example of an oblique-angle barrier constructed upslope of the NOAA Observatory, high on the slopes of Mauna Loa volcano (image from Google Earth).

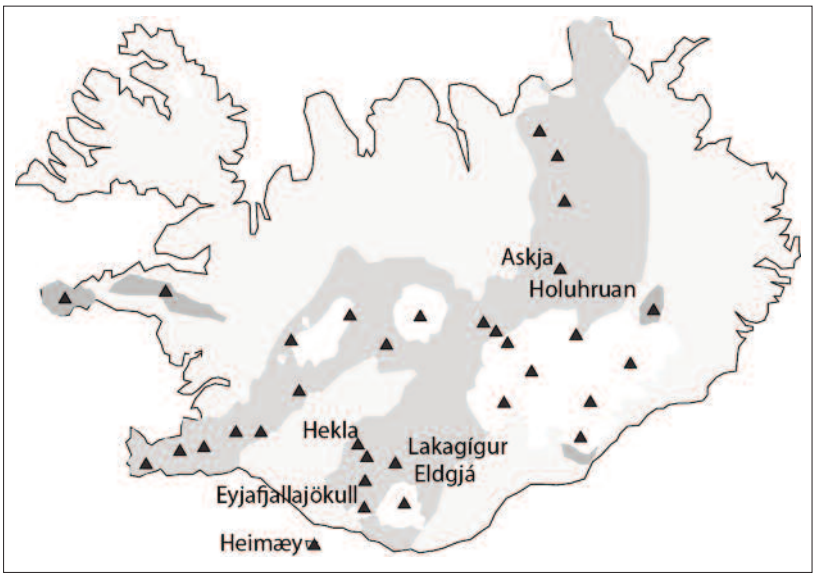
diversion by levee breaching, however, was in Italy in 1992, when breaching was accompanied by construction of a diversion channel. Earthen barriers work to slow flow advance, but are often overtopped. The outcomes of barrier construction are consistent with our experimental results, where flow thickening (and overtopping) are a direct consequence of obstacle construction. During the 1973 eruption of Heimaey, Iceland, local scientists and engineers devised an unusual means of obstacle construction that involved forced rapid cooling of the lava flow. Here the goal was to save a harbour; that goal was successfully met by spraying the advancing lava flow with seawater. As a consequence of lava confinement at the flow front, however, lava backed up (thickened) and then broke out to spread over parts of the town. In summary, our results, when combined with observations of lava flow diversion attempts around the world, suggest that the most effective flow barriers are those that split (and thus slow) individual lava flows, particularly when the barrier forms an oblique angle (Fig. 9). Under these conditions, flow splitting will slow the rate of advance, while the oblique angle of diversion will limit both the increase in flow width caused by the split and the flow thickening that allows barrier overtopping.

Short- and long-term flow impacts

The local impacts of lava flows — particularly inundation of land areas and consequent devastation of plants and the built environment — are obvious, but large lava flow eruptions can also have more far-reaching effects. Over the past three decades, regions downwind of the Kilauea vent have been plagued with 'vog', or volcanic fog, a consequence of the acidic gases emitted from the volcano as they are released from the magma. The detrimental effects of volcanic gas emissions were highlighted during the 2014–15 Holuhraun eruption in Iceland, when a voluminous (more than one cubic kilometre) lava flow eruption released 11 million tonnes of sulphur dioxide (SO_2) into the atmosphere over the six-month duration of eruptive activity (Fig. 10). During this time period, SO_2 levels were sufficiently high to cause respiratory problems in some Icelandic communities. The effects of these large SO_2 emissions could have been worse, except that most of the eruption occurred over the winter, when strong winds rapidly dispersed the gas and winter darkness slowed the conversion of SO_2 to harmful sulphuric acid. The situation was different in June of 1783, when even larger volumes (*c.* 15 cubic kilometres) of lava poured over southern Iceland from Lakigigur (Fig. 10), and released an estimated 122 million tonnes of SO_2 to the atmosphere over the subsequent eight months. The local impacts of the eruption were described by Jón Steingrímsson, a pastor living in southern Iceland, and provide a gripping account of the terrifying effect of this eruption on the local population (Steingrímsson 1998):

> "All week long neither sun nor sky could be seen for the thick clouds of fumes and smoke which blanketed the area.
> "Whenever the sun or moon could be seen on that part of the sky where the fire vapours swirled about, each appeared red as blood.
> "... more poison fell from the sky than words can describe: ash, volcanic hairs, rain full of sulphur and saltpeter, all of it mixed with sand.
> "All water went tepid and light blue in colour and rocks and gravel slides turned grey. All the earth's plants withered and turned grey ..."

Figure 10 Map of Iceland showing the glaciers (in white), the active volcanic zones (in dark gray) and the volcanoes (black triangles). All locations mentioned in the text are shown on the map.



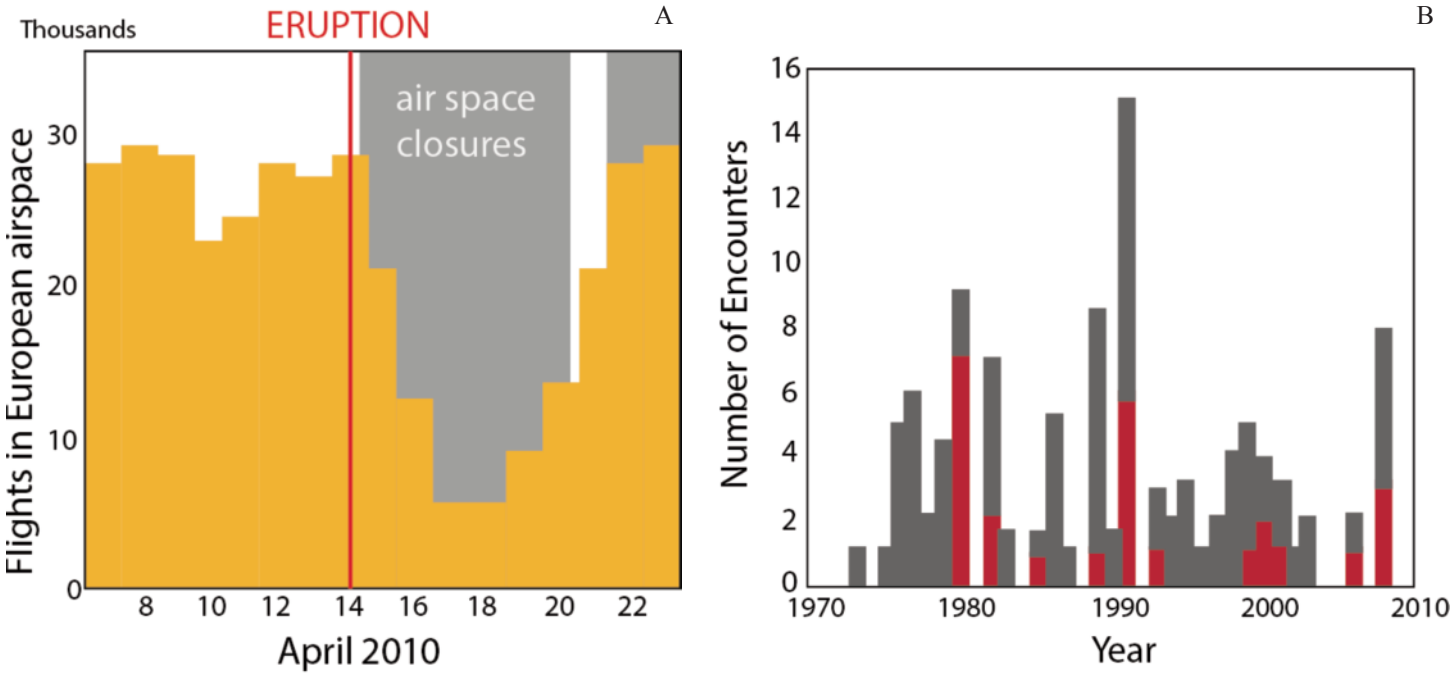


Figure 11 Aircraft encounters with volcanic ash plumes: (A) reduction in flights over Eruopean airspace caused by the April 2010 eruption of Eyjafjallajökull volcano in Iceland (re-drafted from BBC Website); (B) number of aircraft encounters with volcanic ash plumes between 1970 and 2010 — serious encounters are shown in red. Peak in serious encounters in 1980 is related to the eruption of Mount St Helens; peak in total number of encounters in 1991 is related to two major eruptions that year, of Pinatubo, Philippines, and of Hudson, Chile (redrafted from Guffanti et al. *2010).*

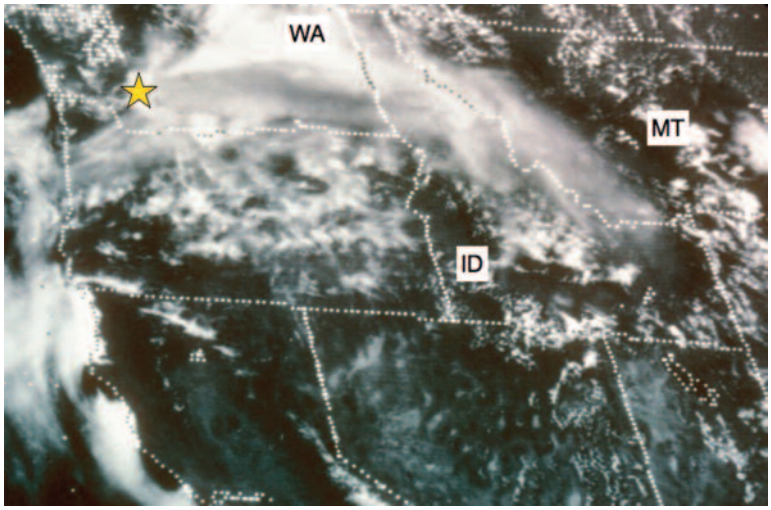
The impact of this eruption on the Icelandic population was disastrous, causing a Haze Famine (Móðuharðindin) that caused crops to fail and killed >50% of the livestock and, as a consequence, 20% of the Icelandic population. Moreover, the combined effect of the high eruption rates, large SO_2 emissions and summer daylight and weather patterns meant the that effects of the eruption were felt much farther afield. For example, a persistent atmospheric haze caused by the eruption lingered over the UK and France for several months, causing respiratory problems, crop failures and high mortality rates. The haze was vividly described by British naturalist Gilbert White (1789), who noted: "The sun, at noon, looked as blank as a clouded moon, and shed a rust-coloured ferruginous light on the ground, and floors of rooms; but was particularly lurid and blood-coloured at rising and setting… the country people began to look with a superstitious awe, at the red, louring aspect of the sun."

Summer in the arctic was unusually cold, and remained so for the following two or three years. The eruption may even have affected the flow of the jet stream, which controls weather patterns throughout the northern hemisphere, and disrupted the Asian monsoon, prompting famine in Egypt.

More recently, Europe has experienced a different manifestation of volcanic hazard from Iceland. The 2010 explosive eruption of Eyjafjallajökull volcano dispersed volcanic ash toward northern Europe; one consequence was extensive closure of airports (Fig. 11A), a disruption that caused losses of *c.* £1 billion. Why was Europe caught off guard? The hazards of ash from explosive eruptions in Iceland were well known, as outlined in a paper by the famous Icelandic volcanologist S. Thorarinsson that he titled 'Greetings from Iceland' (Thorarinsson 1981) and in which he documented ash from several eruptions in Iceland that had reached Sweden. In addition to the effects of the Laki eruption, Thorarinsson provides accounts of ash fall from the large 1875 eruption of Askja volcano, where severe impacts in northeast Iceland contributed to a mass emigration to North America, and the 1947 explosive eruption of Hekla volcano. Ash hazards to civil aviation were also well understood, as summarised in a 2010 paper by USGS geologists that compiles information on 94 confirmed encounters of aircraft with volcanic ash clouds between 1953 and 2009 (Guffanti *et al.* 2009) (Fig. 11B). Until 2010, however, Icelandic volcanoes had not sent extensive ash clouds toward Europe since the rise of the airline industry.

Other parts of the world have experienced more recent disruptions because of volcanic ash. Ash hazards are particularly prevalent in the Americas, where the volcanoes lie along the western margin (the eastern edge of the Pacific 'Ring of Fire'; *see* Fig. 1) and prevailing winds from the west transport ash clouds over the continental landmass to the east (Fig. 12). During the 1980 eruption of Mount St Helens, USA, ash fall extended more than 600km. They are described in a poem by Gary Snyder (2004):

Figure 12 Volcanic ash plume from the 1980 eruption of Mount St Helens (location indicated by yellow star). The plume traversed the states of Washington (WA), Idaho (ID) and Montana (MT), a distance of more than 600km (original photo from NOAA).



"roiling earth-gut-trash cloud tephra twelve miles high
ash falls like snow on wheatfields and orchards to the east
five hundred Hiroshima bombs"

"in Yakima, darkness at noon"

Distal impacts are particularly disturbing because the source cannot be seen and, before the days of rapid long-distance communication, could not even be identified. As a result, rumours abounded in 1980, including fears that the ash was radioactive. This fear stemmed directly from an incident just one year before, when a reactor meltdown at a nuclear power plant in Three Mile Island, Pennsylvania, had caused the most serious commercial nuclear power plant accident in US history.

Going back in time, oral traditions from Native American communities north-east of Mount St Helens record responses to an earlier explosive eruption in 1800 that underline the fear invoked by distal ash fall when the source is completely unknown (Ray 1980): "When my grandmother was a little girl a heavy rain of white ashes fell. The people called it snow... The ashes fell several inches deep all along the Columbia and far on both sides. Everybody was so badly scared that the whole summer was spent in praying. The people even danced — something they never did except in winter. They didn't gather any food but what they had to live on. That winter many people starved to death."

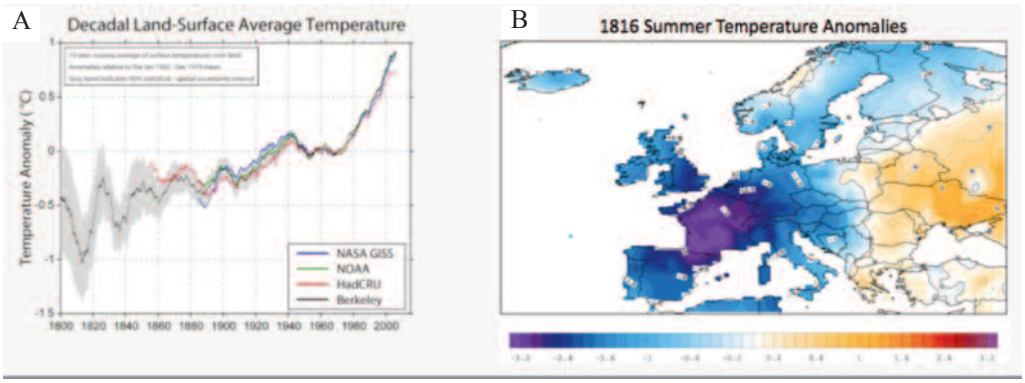


Figure 13 Effect of large volcanic eruptions on global temperatures: (A) decadal variations in average global temperature since 1800 — the decade from 1810–1820 was the coldest of the past two centuries, probably because of two large volcanic eruptions, the 'unknown' eruption of 1808 and the 1815 eruption of Tambora, Indonesia (from Berkeleyearth.org); (B) anomalies in 1816 summer temperatures in Europe caused by the Tambora eruption — the average temperatures in France and the UK were up to 1.5˚C lower than normal (figure from http:// en.wikipedia.org/wiki/Year_Without_a_Summer).

Impacts on temperature

Large volcanic eruptions can have global impacts in the form of temporary perturbations of Earth's temperature. Large explosives inject both fine ash and gases into the stratosphere, where sulphur dioxide gas is oxidised to sulphuric acid, which then condenses to form sulphate aerosols. These aerosols reflect solar radiation back into space, and thus cool the lower atmosphere. A dramatic example comes from the decade of 1810–20, when average global temperatures reached their lowest point in the past two centuries (Fig. 13A). In large part, this temperature anomaly can be attributed to the 1815 eruption of Tambora volcano in Indonesia, the largest eruption of the past several centuries. Interestingly, however, global temperatures had already started to fall in 1809–10. Analyses of ice cores from both Greenland (northern hemisphere) and Antarctica (southern hemisphere) show evidence for a sulphur layer in 1809, which has led to the speculation that an 'unknown' eruption helped to trigger the cold decade. How could there be no historic record of such an event?

To address this question, we teamed up with an historian of colonial Latin America. She searched archival documents and discovered two records that shed some light on the puzzle. The first comes from Francisco José de Caldas, Director of the Astronomical Observatory of Santa Fe de Bogotá, Colombia. A report published by Caldas in February of 1809 described an upper atmospheric stratospheric cloud that had appeared on 11 December 1808 and persisted until the time of the report (Caldas, translated in Guevara-Murua *et al*. 2004): "As of 11 December of last year, the disk of the sun has appeared devoid of irradiance, its light lacking that strength which makes it impossible to observe it easily and without pain. Its natural fiery colour has changed to that of silver, so much so that many have mistaken it for the moon... The stars of the first, second and even third magnitude have appeared somewhat dimmed, and those of the fourth and fifth have completely disappeared, to the observer's naked eye. This veil has been constant both by the day and by night..."

Caldas noted that this atmospheric phenomenon was not restricted to Bogotá, but instead was also reported from other parts of Colombia, consistent with the presence of a widespread volcano-induced stratospheric haze. Caldas also reported uncharacteristically cold mornings, with widespread ice and resulting crop damage. Importantly, at exactly the same time the Peruvian physician Hipólito Unanue reported unusual optical effects at sunset (Unanue, translated in Guevara-Murua *et al.* 2004): "At sundown in the middle of the month of December, there began to appear toward the S.W., between cerro de los Chorillos and the sea, an evening twilight that up the atmosphere. From a N.S. direction on the horizon, it rose towards its zenith in the form of a cone, [and] shone with a clear light until eight [o'clock] at night, when it faded. This scene was repeated every night until the middle of February, when it vanished."

This phenomenon is known as twilight glow; it is caused by light scattering by stratospheric aerosols and has been observed after other large eruptions. Together, these accounts from both north (Colombia) and south (Peru) of the equator, at exactly the same time, provide strong evidence of a large tropical eruption, most likely in early December of 1808. Although we have not been able to identify the volcano, the most likely location for such an eruption is Indonesia, with its high density of frequently active volcanoes.

The climate disturbance initiated by the 1808 eruption was magnified by the eruption of Tambora in 1815, an enormous eruption that created a stratospheric veil observed throughout the United States. The following year, extreme cold throughout the northern hemisphere (Fig. 13B) caused the 'Year Without a Summer', when failed harvests throughout Europe caused widespread famine, and failed harvests and famine in India accompanied resultant changes to the Asian monsoon. The dreariness of

the summer weather is recorded in Lord Byron's poem 'Darkness' (1816):

"I had a dream, which was not all a dream.
The bright sun was extinguish'd, and the stars
Did wander darkling in the eternal space,
Rayless, and pathless, and the icy earth
Swung blind and blackening in the moonless air;
Morn came and went — and came, and brought no day,
And men forgot their passions in their dread
Of this their desolation; and all hearts
Were chill'd into a selfish prayer for light..."

Accounts of similar stratospheric dust veils can be traced back through time, and along with them evidence for severe global impacts of past eruptions. For example, the atmospheric effects of a large eruption of Ilopango volcano, El Salvador, in AD 536 are described by the Roman official Cassiodorus in Ravenna, Italy, who describes a "blue-coloured sun" and a "summer without heat" and with both "perpetual frost and unnatural drought" (quoted in Graslund and Price 2012). In fact, tree ring records from North America suggest that the entire decade from AD 536 to 545 was unusually cold, with one severe temperature perturbation in 536 and another in 540–542. This decade of cold with two obvious cool spikes suggests another example of paired large eruptions.

Archaeologists have connected severe weather in the mid-6th century AD to a major collapse of Viking settlements in east central Sweden (Fig. 14) and, as a result, initiation of the Migration Period and Viking diaspora (Graslund and Price 2012). They further suggest that oral traditions of this time are preserved in the Icelandic sagas, specifically in tales of Ragnarök (commonly translated as the Twilight of the Gods) that are found in the 13th-century *Eddas* of Snorri Sturluson. Ragnarök is forecast for the future but appears to be derived from memory of a past event, when (Sturluson, translated in Scudder 2001):

"[The wolf] smears with red blood
the gods' heavenly site
the sunshine was black
for summers after
the weather treacherous"

This is only the start of Ragnarök, which manifests as: "a winter… called Fimbulwinter. Then snow will drift from all directions. There will then be great frosts and keen winds. The sun will do no good. There will be three of these winters together and no summer between." (in Graslund and Price 2012; from Faulkes 1987):

This sequence of harsh winters is followed by another event, when (Sturluson, translated in Scudder 2001):

"The sun turns black,
land sinks into the sea,
the bright starts
vanish from the sky.
Fire rages forth
at the life-giving tree,
high flame will lick
at heaven itself."

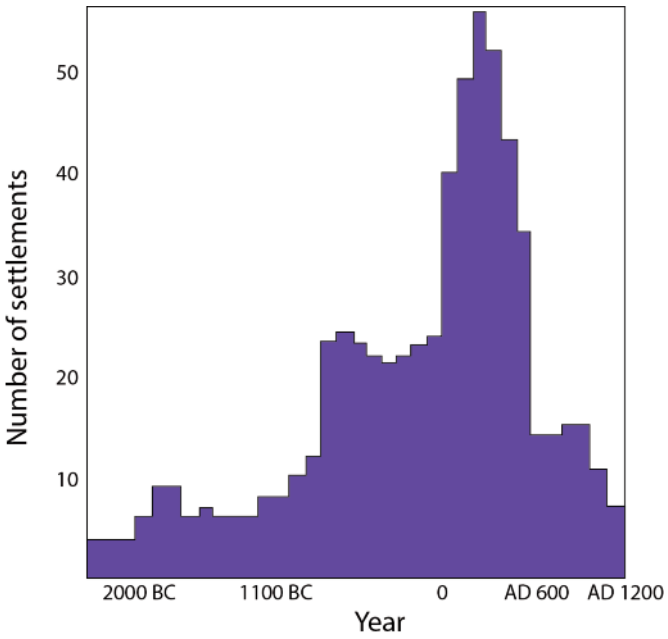


Figure 14 Settlement patterns in east central Sweden. Note precipitous drop in settlement numbers before AD 600, coincident with (and inferred to be driven by) a documented cold period in the mid-6th century caused by the AD 536 eruption of Ilopango volcano, El Salvador, and possibly a second eruption c. *AD 540 (redrafted from Graslund and Price 2012).*

This imagery is much more immediate, and may well recall an enormous Icelandic eruption three centuries before the *Poetic Edda* were collected in writing. The AD 934 eruption of Eldgjá (which loosely translates as 'Fire chasm') sent 25% more lava than the 1783 Laki eruption into Iceland's south-central coastal plains. Although there is no written record from Iceland during this time period, an account from northern Germany appears to record this event (quoted in Stothers 1998): "Indeed before the death of King Henry [2 July 936] many prodigies occurred, such as: The brightness of the Sun outdoors in a cloudless sky appeared almost nil, but it streamed indoors, red as blood, through the windows of the houses. Likewise for the mountain where the overlord of the states was buried, according to report, because the mountain erupted in flames in many places."

Although the identity of the 'overlord of the states' is unclear, it could be a direct reference to Iceland with the overlord being Úlfljótr, who held the position of the first lawspeaker of the united Icelandic parliamentary body (the *Alþingi*), which was formed in the last year of settlement. Not surprisingly, the Eldgjá eruption apparently brought the Icelandic settlement period to an abrupt end, only 60 years after it started.

Summary

To summarise, volcanic eruptions occur frequently around the world. Where eruptions are common and of relatively low intensity (e.g., lava flows), humans not only co-exist with their restless environment but may also attempt to control it. Larger eruptions are less frequent, but have much greater impacts. Unlike earthquakes or floods, where impacts are local to regional in scale, the impacts of volcanic eruptions span from local to regional to even global. The far-reaching impacts have had substantial impacts on past societies, impacts that have caused crop failures and famines. These extreme impacts have provoked

extreme responses in societies substantially affected by famine, or even those seeking explanations for the 'portents' of falling distal ash or stratospheric veils that caused the sun to appear dim and without heat.

Today, many volcanoes in the world are monitored, either locally via networks of seismometers, GPS sensors and gas detection instruments, or globally using satellites. Satellite-based systems, in particular, provide a global means of monitoring precursory changes in the Earth's surface, early release of volcanic gases before eruption onsets, and movement of clouds of volcanic ash and gas as they are dispersed from volcanic vents. Not only news, but also hundreds of photos of eruptive activity fly around the Internet, providing instant global updates of volcanic crises. Modern technology cannot, however, change the nature of volcanic eruptions, and our highly interconnected world is also highly susceptible to disruption by volcanic activity, as illustrated by the 2010 eruption of Eyjafjallajökull volcano in Iceland. Moreover, it is clear that the far-reaching effects of very large eruptions — including decreases in global temperatures and consequent impacts on regional food and water supplies — would still reverberate around the globe. For this reason, the challenge for both volcanologists and people living in regions with the potential to be affected by volcanic activity is to develop strategies to improve resilience to the local, regional and global effects of volcanic eruptions.

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Table 1 Summary of historical diversion attempts

year	*location*	*style*	*effect*
1669	Mount Etna, Italy	levee breach by excavation	incomplete attempt
1935	Mauna Loa, USA	aerial bombing of lava tube	minor breakouts, eruption ceased soon after
1942	Mauna Loa, USA	aerial bombing of levees	created a temporary branch that rejoined the main flow after a short distance
1955	Kilauea, USA	earthen barriers	partly successful at detection
1960	Kilauea, USA	earthen barriers	barriers overtopped or undermined
1973	Heimaey, Iceland	water-cooling	flow front stalled and thickened, habour saved
1983	Mount Etna, Italy	earthen barriers, levee breach by explosives	barriers diverted the flow but were overtopped; levee breach failed but debris created in the attempt did cause significant overflows
1991–3	Mount Etna, Italy	earthen barriers, levee breach by explosives	barriers delayed flow advance but were overtopped; levee breach was successful
2001	Mount Etna, Italy	earthen barriers	numerous barriers delayed advance and diverted the flows; many overtopped

OUGS Symposium, Newcastle 2015: Pangaea: Life and Times on a Super Continent: a celebration of Britain's unique marine Permian strata

Pangaea and the Permian geology of north-east England

Paul F. V. Williams

Introduction

This paper presents an overview of the events leading up to the formation and development of the supercontinent of Pangaea and provides an introduction to the Permian geology of north-east England, which developed on a part of the Pangaean continental landmass. In particular it focuses on the unique marine strata that were laid down over parts of northern Pangaea in the later stages of the Permian, remnants of which remain preserved and exposed today in north-east England.

A general overview of the marine Permian succession is given in Williams (2015)), and the geology covered by Robson (1965). For an in-depth discussion of the numerous Permian Geological Conservation Review sites in north-east England the reader is referred to Smith (1995) for the necessary detail.

The development of Pangaea and the framework for Permian sedimentation in north-east England

Across the bulk of the British Isles the Permo-Triassic succession is represented by a series of mainly continental red beds or shallow fluvial clastics deposited under a hot, arid climate. In north-east England, however, in contrast to the rest of Britain, unique marine sediments make up a large part of the late Permian succession (Fig. 1).

Figure 1 The marine Permian Succession in north-east England: Cliffs of Roker Formation Dolomites at Halliwell Bay, Co Durham.

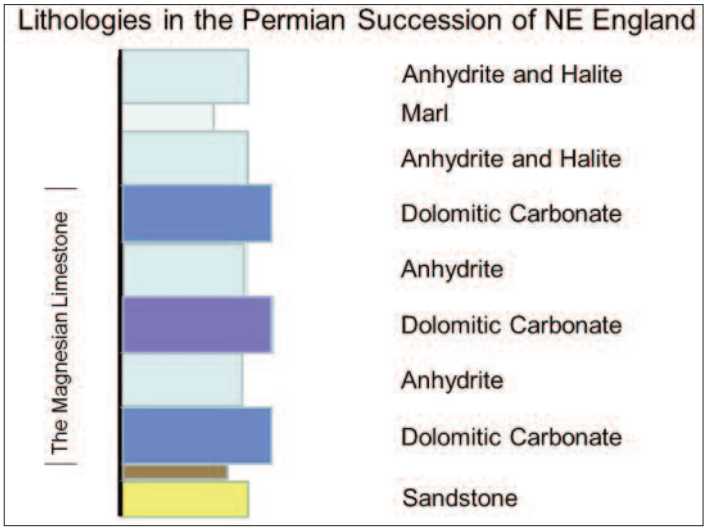

Figure 2 Generalised Late Permian lithostratigraphy of north-east England.

When we look broadly at the lithologies of these marine sediments in north-east England we see an alternation of marine carbonates and evaporites (Fig. 2). To understand the reasons for this marine and cyclic sedimentation we need to look back to events taking place in the later part of the Carboniferous Period.

During a large part of the Upper Carboniferous Period global compressional tectonics were in operation, manifesting themselves in the various phases of the Variscan Orogeny. Across north-west Europe and south-west Britain compressional axes trending approximately in an east–west direction were effectively suturing the ancient Caledonian cratonic areas of Britain to north-western Europe. This was a local expression of a global series of tectonic movements that ultimately resulted in the suturing of continents into one supercontinental landmass: Pangaea. The northerly hemisphere of Pangaea was made up of an amalgamation of the continental crustal units of Laurentia and Baltica, termed Laurussia; the continental landmass of Gondwana formed the southern aspect of the supercontinent (Fig. 3, *overleaf*)

Once Pangaea had formed, the tectonic style of the northern hemisphere changed, aided in part by post-Variscan thermal relaxation, from one of compression to one of extension and transtension.

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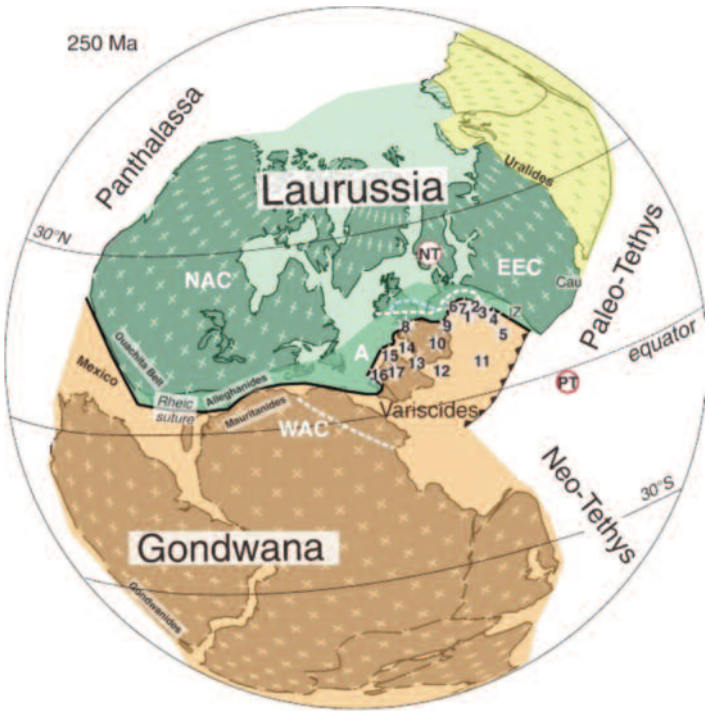
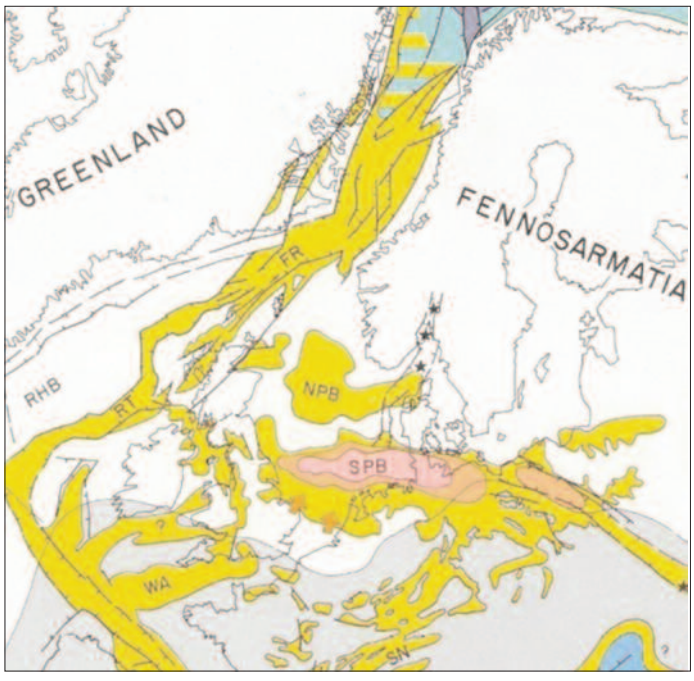


Figure 3 The assembly of Pangaea after the Variscan Orogeny and the position of Laurussia in the Northern Hemisphere (after Kroner and Romer 2013, with permission; this image was published in Kroner, U., and Romer, R. L. 2013 'Two plates — many subduction zones: the Variscan orogeny reconsidered'. Gondwana Res *24, 298–329, fig. 1 — © Elsevier 2013)*

This resulted in the formation of a number of rift and strike-slip subsiding basins across Laurussia (Fig. 4). It also facilitated widespread decompressive mantle melting to source mafic magmas, which were emplaced across many parts of Laurussia. Mafic sill suites developed across Scandinavia (the Oslo Rift) and, closer to home, sourced the Scottish Midland Valley sill and dyke complex and the Whin Sill complex of northern England (McCann *et al.* 2006).

As a result of the continuing Pangaean extensional tectonic regime a number of subsiding intracratonic strike-slip basins developed in the area that was to become Britain and the surrounding



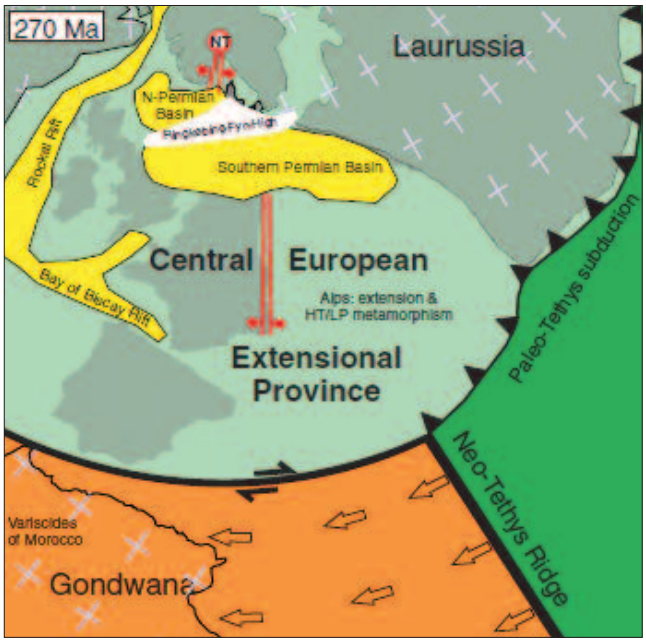


Figure 4 Development of the Early Permian Extensional Tectonic Province over Laurussia (after Kroner and Romer 2013, with permission; this image was published in Kroner, U., and Romer, R. L. 2013 'Two plates — many subduction zones: the Variscan orogeny reconsidered'. Gondwana Res *24, 298–329, fig.10 — © Elsevier 2013).*

North Sea region. These basins depressed the Pangaean land surface below general sea level, and these areas are identified in Figure 5.

For much of the early Permian continental desert sedimentation ensued across the landlocked hot, arid plains and depressed basins of Laurussia; and in the area that was to become Britain, then situated at around latitude 20˚ north, a series of red continental clastics developed. In present-day north-east England a series of linear dunal sand ridges can be identified within the earliest Permian deposits. These oldest units of the Yellow Sands Formation overlie the Carboniferous strata (Fig. 6, *opposite left*) and form a narrow NNW–SSE outcrop at the westerly edge of the Permian strata in north-east England. They comprise a series of poorly cemented sands of Early Permian age with rounded, 'millet seed' sand grains which characterise their desert origins. They show classic dune bedding structures and are never more than *c.* 60m thick, although the formation is very variable in thickness locally. By mapping these thickness variations the morphology of the dunal sand ridges can be identified and are found to align with the prevailing east-north-easterly palaeo-wind direction, giving clues to the earlier Permian palaeogeography of the region.

By late Permian times, global sea levels were rising due to southern hemisphere deglaciation. As a result of this sea level rise — coupled with continuing extensional tectonics, rifting and subsidence in the northern part of northern Pangaea — a connection was eventually established between the low-lying intracratonic Permian basins and the northerly Boreal Ocean through a narrow, restricted seaway (Fig. 7, *opposite right*). These interconnecting straits were likely to have had a silled connection with the open ocean. Rapid flooding ensued across these low-lying Permian basins, creating a shallow land-locked epicontinental sea, the

Figure 5 Tectonic map of north-west Europe in the early Permian showing the development of subsiding intracratonic strike-slip basins over the Pangaean continental land surface (after Gast and Gundlach 2006, fig. 1, with permission; © ZDGG 2006; www.schweizerbart.de).

Figure 6 Unconformity between Upper Carboniferous sandstones, partly desert-reddened, and early Permian Yellow Sands Formation; exposures at Castletown on the banks of the River Wear. Hammer lies on the undulating unconformity surface. Carboniferous strata dip downwards to left of picture.

Zechstein Sea, with two distinct, defined South and North Permian Basins (Fig. 8). The scene was now set for marine sediments to accumulate in the Permian basins, and along the eastern edge of the developing British mainland.

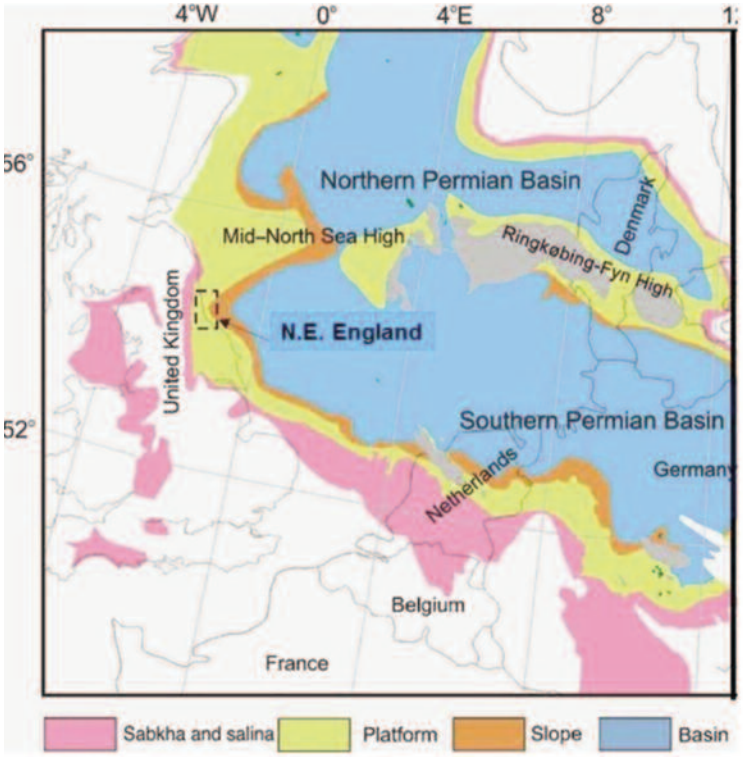
Another intriguing aspect of the late Permian sedimentary history of north-east England is the cyclic nature of the deposits, with alternations of marine carbonates and evaporites forming three major, well-defined cycles. The explanation for this lies in the unique combination of climate, ongoing tectonic changes and continuing oscillations of global sea level operating in the late Permian and affecting depositional conditions over the Zechstein Basin.

The silled connection between the Zechstein Sea and the Boreal Ocean was sensitive to fluctuations in sea level and bathymetric changes at the mouth. A fall in sea level or tectonic uplift could bring about isolation of the basin from oceanic circulation and recharge. During the Late Permian a greenhouse climate predominated with elevated surface temperatures. Under this hot, arid climate evaporative drawdown resulted in the development of hypersalinity of Zechstein seawater, and the precipitation of evaporites. Further rifting and subsidence at the mouth of the basin, on the other hand, or sea level rise resulted in re-establishment of the connection to the open ocean, recharge of the basin and restoration of more normal salinity terminating evaporite deposition and a return to carbonate sedimentation. Studies of carbon and oxygen isotopes in Zechstein carbonates suggest that palaeoclimatic instability may also have been a contributing factor, with periods of wetter climate and precipitation increase coincident with some of the carbonate horizons in some parts of the Zechstein Basin (Gasiewicz 2013). Periodic oscillations in global sea level and bathymetry at the mouth of the interconnecting seaway produced episodes of basin isolation, during which time evaporite deposition occurred, resulting in repeated carbonate-evaporite cycles.

The final major intrigue of Late Permian sedimentation in north-east England is the dominance of dolomitic rocks in the carbonate succession. The vast majority of the carbonate rocks are dolomites and dolomitic limestones, with true limestones

Figure 7 Map of the northerly Pangaean land surface in the Late Permian with present-day continental margins of north-west Europe included for reference, showing the formation of the Zechstein Sea and position of Sub-Basins and Highs. Cratonic areas of Scandinavia and Greenland in approximate Late Permian positions.

Figure 8 Map of north-west Europe in the Late Permian showing the position of the Southern Permian and Northern Permian Zechstein Basins and their palaeogeography (modified after Slowakiewicz et al. *2013, fig. 1, with permission; original figure AAPG©2013, reprinted by permission of the AAPG whose permission is required for further use).*



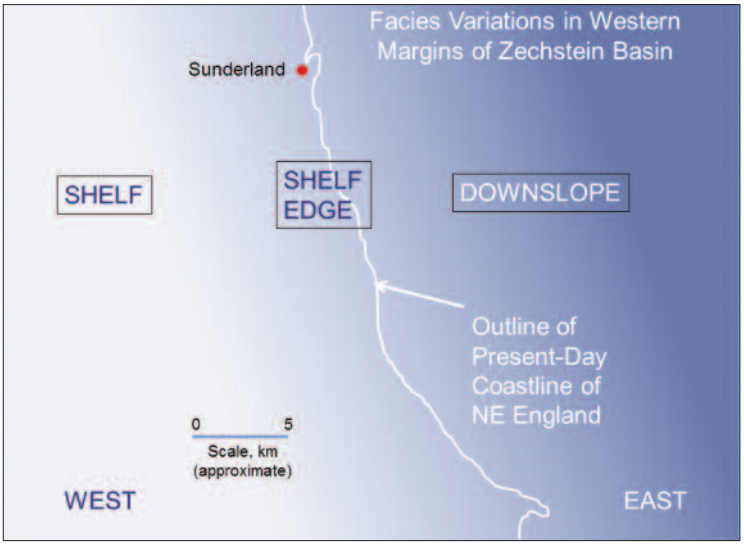


Figure 9 Facies variations in Zechstein sediments across north-east England delimiting shelf, shelf edge, and basin downslope depositional palaeoenvironments at the western margins of the Zechstein Sea.

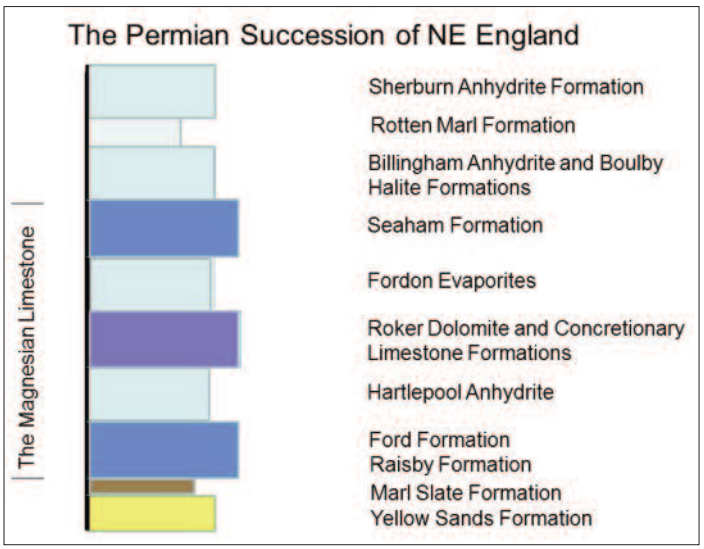


Figure 10 The Permian Succession in north-east England — dark blue ornament represents carbonate facies (not to scale).

poorly represented, although some of the original dolomites have been converted to limestones (technically de-dolomites) by later changes. During the Permian the oceans surrounding the Pangaean continent had magnesium concentrations much higher than those of more normal oceanic waters. (Lowenstein *et al*. 2005). In these 'aragonite seas', as they are known, aragonite would be the primary carbonate precipitated, and further increases in salinity reflected by dolomite or high-Mg calcite formation rather than ordinary calcite. It is believed that the establishment of aragonite seas with elevated Mg concentrations reflected the absence of major global sea floor spreading activity over the vast supercontinent, since rapid sea floor spreading is the site where magnesium is usually recycled. Once the rifting and break-up of Pangaea ensued, sea floor spreading activity would have increased again, leading to magnesium recycling through volcanic processes and return of oceans to less extreme Mg levels. Climate, temperature and sea level are also known to affect sea water ionic compositions, with cool icehouse conditions also favouring aragonite precipitation, precisely the conditions prevalent during the early Permian, especially at southern latitudes.

The marine Permian succession of north-east England

It was thus a chance combination of factors that facilitated the deposition of north-east England's unique marine Permian succession. The area of land that was eventually to become north-east England was situated on the extreme western edge of the Zechstein Basin, and where it is preserved today in the sediments, it is a record of the history of the shelf-edge and basin-slope environments of the Zechstein Sea.

Figure 11 Collapse breccia composed of blocks of Roker Formation Dolomite, resulting from dissolution of underlying evaporite horizons, Roker Formation, Halliwell Bay, Co Durham (walking pole is 1m high).

Variations in sedimentary facies are recognised across the Permian exposures of north-east England, reflecting Permian basin margin bathymetry. Shallow water shelf and shelf-edge sediments found more westerly, with deeper basin-slope sediments developed to the east (diagram, Fig. 9).

The general sedimentary succession for north-east England shown in Figure 10 comprises several well developed, thick dolomitic carbonate horizons known locally and collectively in older terminology as 'The Magnesian Limestone' (shown in dark blue in Fig, 10).

This generalised succession is, however, only seen in offshore boreholes. For all onshore successions the intervening evaporite horizons have all been lost either due to later dissolution — and are now only

represented by centimetre-scale thicknesses of 'dissolution residue' — or were never deposited shorewards in the first place. The loss of many tens of metres of sediment has had profound effects on the overlying Permian strata, which have foundered and collapsed, and are represented in many places by spectacular collapse breccias (Fig. 11, *previous page*).

The full succession nomenclature and strata thickness is given in Figure 12, and extent of the Permian rocks outcropping in north-east England is shown in Figure 13, *overleaf*).

All the formations dip gently eastwards over the eroded pre-Permian land surface and form a prominent west-facing escarpment where the Permian sediments rise from an eroded clay vale of soft upper Carboniferous rocks. Thus the younger, upper Permian, beds are found closer eastwards towards the present-day coast. This is demonstrated in the section superimposed on the landscape image in Figure 14.

The initial deposits of the new Zechstein Sea, formed over the early Permian continental clastics of the Yellow Sands Formation, were the fine-grained laminated dolomitic siltstones of the Marl Slate Formation. The Zechstein transgression reworked the top surface of the earlier Permian sands and planed-off the sand dunes formed on the desert basin. In some places the Marl Slate is banked over the dunal sand ridges, and in other areas it is attenuated over them.

The grain-size of the sedimentary particles and consistent parallel planar lamination suggests an environment that was free of currents, meaning that these deposits were below wave base; and also probably points to an almost tideless sea. The sediments are also bituminous, and contain abundant well-preserved fossil fishes, indicative of anoxic bottom-conditions and a stratified water column. Basin morphology is likely to have facilitated stratification of the water column, and a barred basin is suggested, with water depth of possibly up to 300m.

The Marl Slate outcrop follows the line of outcrop of the Yellow Sands (Fig. 13), and is never more than 6m thick; and occasionally not present at all. It has yielded a rich fauna of early fossil fish (Fig. 15) and land plants, and a unique gliding reptile — *Coelurosauravus jaekeli* — thought to be a forerunner of flighted animals (Fig. 16).

Current Terminology (D.B.Smith 1995)	Former Terminology BGS	Maximum Thickness, m
Sherburn Anhydrite Fm.		4
Rotten Marl Formation		10
Boulby Halite/Billingham Ahydrite Formations		70
Seaham Formation Fordon Fm.	Upper Magnesian Limestone	33 10 onshore;
Roker Dolomite Formation	Upper Magnesian Limestone	200
Concretionary Limestone Formation	Upper Magnesian Limestone	116
Hartlepool Anhydrite Formation	Middle Magnesian Limestone	Residue onshore 130 offshore
Ford Formation	Middle Magnesian Limestone	116
Raisby Formation	Lower Magnesian Limestone	76
Marl Slate Formation		6
Yellow Sands Formation		~60 max

Figure 12 Permian stratigraphy and nomenclature for north-east England, and thickness of stratigraphic units.

Figure 14 Permian strata forming landscape and topography in Co Durham: view looking north with general geological section superimposed; west-facing escarpment edge clearly visible to west (surmounted by Penshaw Monument), together with the surface expression of the Ford Formation reef facies farther east; foreground is composed of drift and coal measures sediments.

Figure 15 Fossil fish with jawbone, Marl Slate Formation. Pygopterus *sp., Quarrington Quarry, Co Durham.*

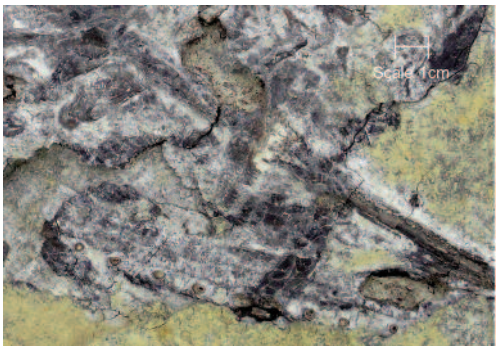
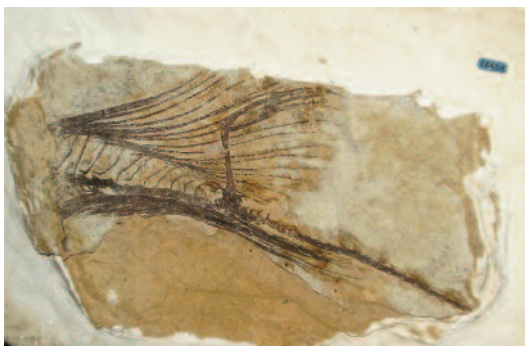


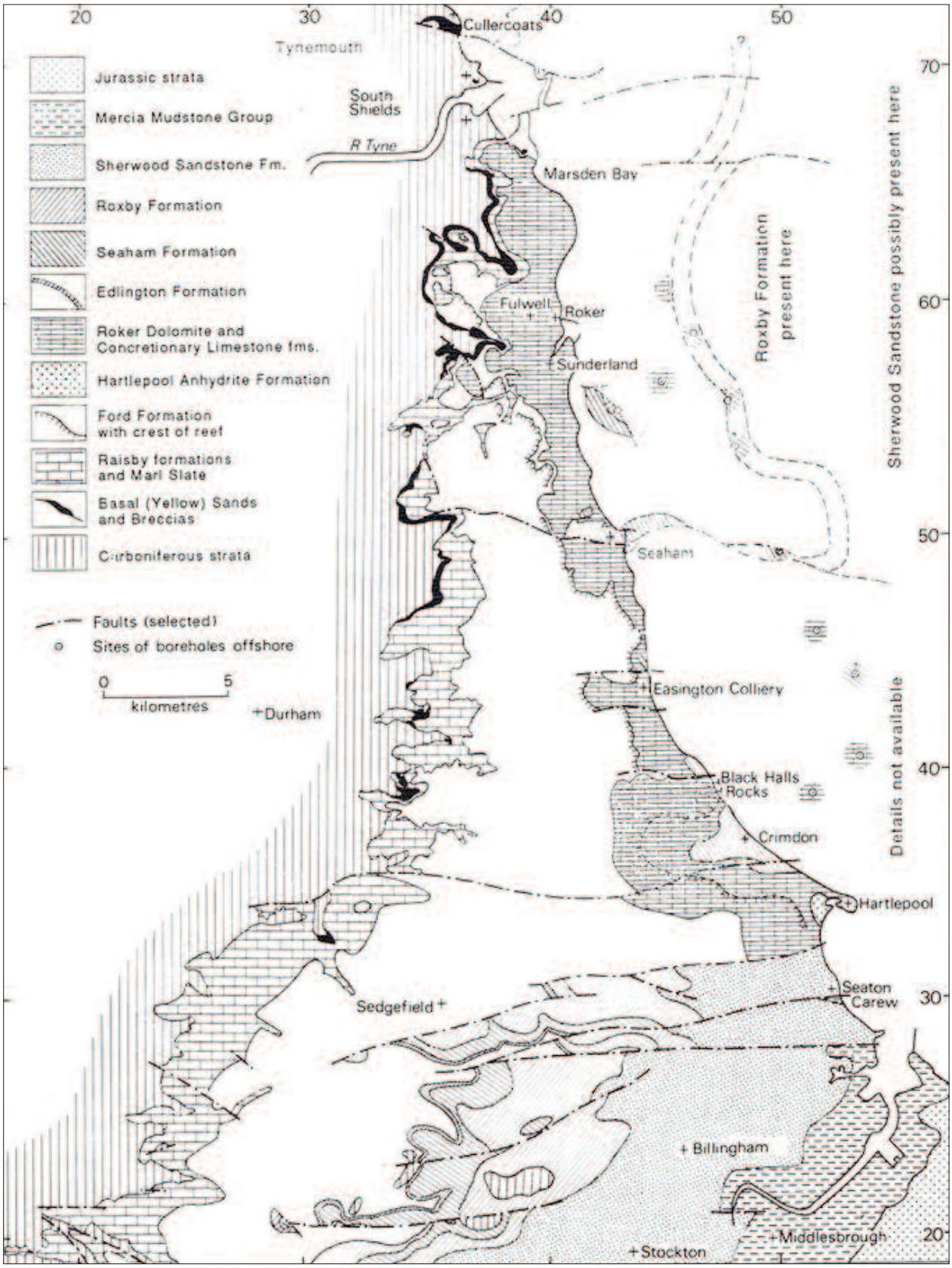
Figure 16 Coelurosauravus jaekeli*, a gliding reptile, thought to be the forerunner of flighted creatures — Marl Slate Formation, Eppleton Quarry, Co Durham (specimen in Sunderland Museum).*



The first marine carbonates of the Zechstein Sea are deposited over the Marl Slate Formation, heralding the start of the 'Magnesian Limestone' succession. In recognition of the cyclic nature of the carbonate/ evaporite units in the Permian succession of north-east England, a terminology has been developed to classify and identify individual cycles, as detailed in Figure 17 *(opposite)*.

The first carbonate unit of the Zechstein Sea, the Raisby Formation (EZ1a stage — 'Lower Magnesian Limestone') forms a prominent west-facing escarpment, which is a major topo-

Figure 13 Distribution of the Permian outcrops in north-east England (after Robson 1995, fig. 10, with permission; original figure © Natural History Society of Northumbria 1995).



CURRENT TERMINOLOGY (D.B. Smith 1995)	SUB-CYCLE	MAIN CYCLE
Sherburn Anhydrite Fm. Rotten Marl Formation		EZ4
Boulby and Billingham Evaporites Seaham Formation	EZ3a	EZ3
Fordon Evaporites Roker Dolomite Formation Concretionary Limestone Formation	EZ2a	EZ2
Hartlepool Anhydrite Formation	EZ1b	EZ1
Ford Formation		
Raisby Formation	EZ1a	
Marl Slate Formation		
Yellow	Sands	Formation

Figure 17 English Zechstein Cycles terminology.

graphic feature running north-north-west through Co Durham. Deposition of these earliest carbonate units was accompanied by erosion, and the Raisby dolomites are deposited over the Marl Slate, which is thinned and cut out locally by pre-Raisby erosion. They are generally well-bedded, pale-cream-to-buff coloured dolomites displaying parallel bedding on a scale of 100–200mm, and show dissolution cavities in places (Fig. 18). The Raisby beds show evidence of uniform low-energy, tranquil conditions, with little current or wave activity, suggesting a moderate-depth, distally-steepened carbonate ramp into a more basinal, depositional environment. The more thin-bedded finely laminated dolomitic horizons within the formation point to a deeper water, significantly more basinal setting at the far distal end of the ramp.

The formation presents a narrow outcrop width at the western edge of the Magnesian Limestone strata and is developed to a maximum of *c.* 76m, and contains a sparse, shelly marine fauna. Basin submarine slope-failures and gravity debris-slides are recognised at horizons within the Raisby Formation, evidenced from the presence of jumbled units of relatively shallow-water shelf facies surrounded by finer-grained, laminated deeper-water sediments.

More massive-scale events at the end of Raisby times are also recorded, in which the whole thickness of both Raisby and underlying Permian strata has been involved in wholesale movement. The 'Downhill Slide', as it is known, is named from its recognition in the former Downhill Quarry near Sunderland, and it generally affected the more northerly outcrops of the formation, which were involved in the north-eastwards downslope movement of Raisby and underlying units, creating massive submarine slide canyons on the Zechstein seabed. The resultant olistoliths can be seen in the exposures at Trow Point, and also low in the section at Claxheugh Rock, where 'grooves' in the underlying sediments are probably preserved remains of the slide base. The presence and preservation of these slide units and submarine

Figure 18 Raisby Formation overlying dune-bedded Yellow Sands, Coldknuckles Quarry.

Figure 19 Tunstall Hill and the Ford Formation reef crest above Sunderland suburbs

Figure 21 Pre-reef to reef transition — Ford Formation, Humbledon Hill Quarry SSSI.

canyons is regarded as unique, both in Britain and in the marine Permian geology of Europe.

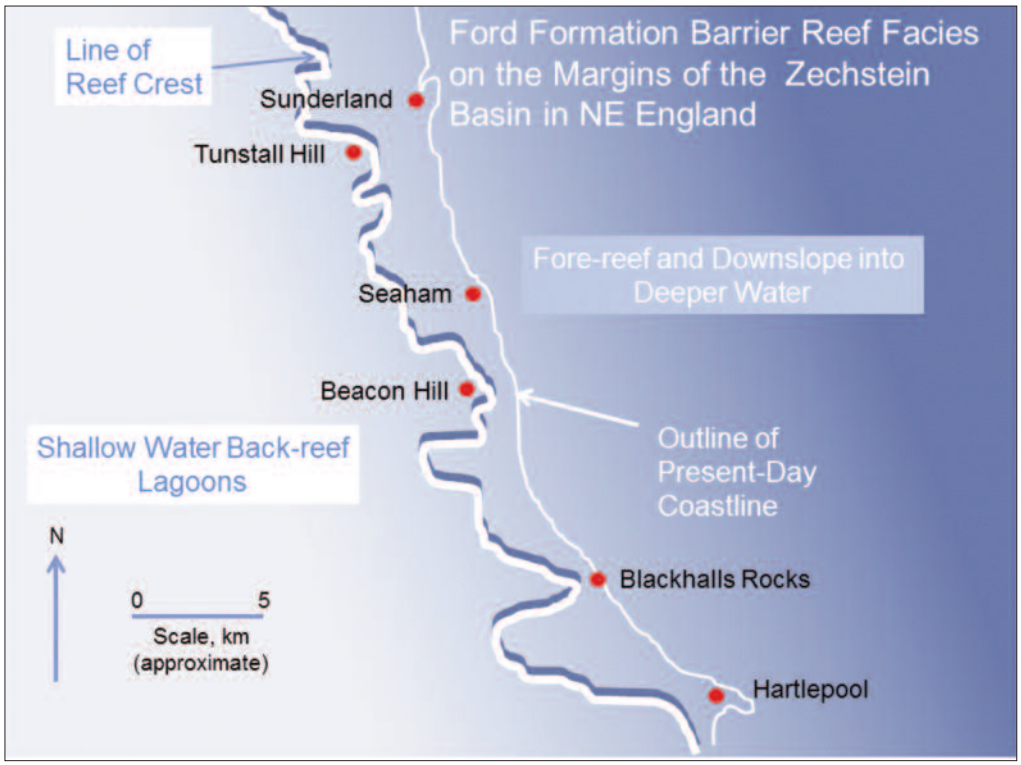
Overlying the dolomites of the Raisby Formation is a series of rocks belonging to the Ford Formation, deposited in the EZ1b cycle. This series is another predominantly dolomitic carbonate unit attaining a maximum thickness of *c.* 116m. The formation shows a wide extent of outcrop from west of Sunderland across much of the East Durham Plateau, outcropping along the coast south of Seaham, Three main facies units can be identified in the Ford Formation across a west-to-east transect of the outcrop, facilitating the interpretation of the depositional environment for the whole unit.

Strata of the Ford Formation developed in the more westerly parts of the region show the presence of ooidal carbonate grainstones, with cross-stratified units and generally an overall coarse grain size, indicating a relatively shallow, higher-energy environment, and points to a shallow lagoonal/marginal shelf setting.

Farther east, however, the formation is represented by a series of more erosion-resistant, unstratified framestones and boundstones with a rich fossil biota, the outcrop of which forms a major topographic feature. These units have been identified as forming the core of a remarkable barrier reef structure. The reef developed on the western margins of the Zechstein Sea shelf area, and its remnants are well defined in north-east England as a prominent topographic ridge. It forms a discontinuous feature running NNW–SSE through Co Durham close to the present-day coastline as a series of linked knolls in the landscape (Fig. 19). The extent of the present-day reef outcrop is shown in Figure 20.

In Permian times the shelf-edge barrier reef is likely to have been a continuous feature running for over 30 km along the margins of the Zechstein Sea basin, with the back-reef shelf area probably stretching westwards for between 5 and 10 km.

Figure 20 Position of the Ford Formation Barrier Reef crest and associated facies in north-east England.



Eastwards of the main reef structure the formation is represented by much thinner, finer-grained planar bedded and thinly laminated dolomites, which in places contain broken and jumbled reef blocks and fossil debris characteristic of the Ford Formation. This is regarded as reef talus deposited downslope in a fore-reef setting, with reef material eroded from the reef crest by wave action. It is thought that water depths here in the fore-reef environment were possibly *c.* 100m deep, compared with the 5m or so over the reef crest.

The reef facies is developed over planar stratified dolomitic mudstones/wakestones, and in some places the transition from pre-reef to reef facies can be well seen, particularly at Humble-don Hill Quarry SSSI (Fig. 21). Some sections at the base of the reef show it to be founded on a shell-bed coquina, pointing to pre-reef shell banks and an already-shallowed marine shelf bathymetry prior

Figure 22 Unstratified Ford Formation reef boundstone, Humbledon Hill Quarry SSSI.

to reef development. It also suggests that there was a transition from the very hypersaline waters of the Raisby beds to one of lower salinity, allowing a wider faunal range to develop.

The unbedded unit of the Ford Formation comprising the reef-core is massive and much harder than the underlying stratified dolomites. On examination it is found to be composed of the remains of numerous shelly organisms, and is richly fossiliferous. The sediments are mainly represented by framestones and boundstones (Fig. 22), and the main reef-building organisms of this remarkable structure were bryozoa, The Permian reef supported a vast array of species, particularly gastropods, bivalves, brachiopods and echinoderms, and fossils of these creatures are abundant in the reef rock (Figs 23 and 24). Some of the reef material shows isolated units of finely laminated horizons, on a scale of tens of centimetres, identified as algal laminites. These also lived encrusted on and around the reef, contributing to the reef structure; and laminites are locally abundant in the reef-crest sediments in several places. During its life the reef was probably in the order of 100m high at its margins, with the deeper, more easterly parts of the basin. At some localities a lateral transition can be seen from the unbedded massive reef-rock of

Figure 23 Fenestellid reef-forming bryozoan, Ford Formation reef facies, Beacon Hill.

the reef crest, to bedded off-reef deposits, as at the type-locality of Ford Quarry in Sunderland.

Westward of the reef core, generally, the outcrops of off-reef bedded strata are ooidal grainstones displaying cross-stratification indicative of deposition under strong current and wave action. Where they are at similar stratigraphic level as the reef crest, these bedded dolomites are interpreted as back-reef deposits on the shallow landward side of the main reef. As the reef grew the back-reef lagoons continued to build upwards too, maintaining a difference in height of *c.* 5m between reef crest and lagoon floor.

Exposures of the massive reef-rock have in the past yielded numerous fossils, in particular at Humbledon Hill Quarry (Fig. 22), Tunstall Hill and Ford Quarry. The Humbledon Hill site is historically significant for the many unique figured and cited fossil specimens collected by the Victorian pioneers of Permian geology in north-east England, in particular King, Howse and Kirkby (Egeland-Eriksen 2016).

Among what appears to be a relative uniformity in the three major facies units of the Ford Formation described above, another more localised, but distinctive, unit also needs mention. Along the coast of South Shields from Frenchmans Bay to Trow Point are a series of intriguing exposures of undoubtedly Ford Formation lithologies. The Trow Point Bed is a basin floor deposit of no more than 0.6m maximum thickness, comprised of laminated dolomitic beds containing columnar algal stromatolites. This remarkable unit is widespread and persistent, being

Figure 24 Ford Formation reef fossils: top — gastropods, Ford Quarry; bottom — reef biota. Humbledon Hill Quarry SSSI (scale-bar for each in lower image).

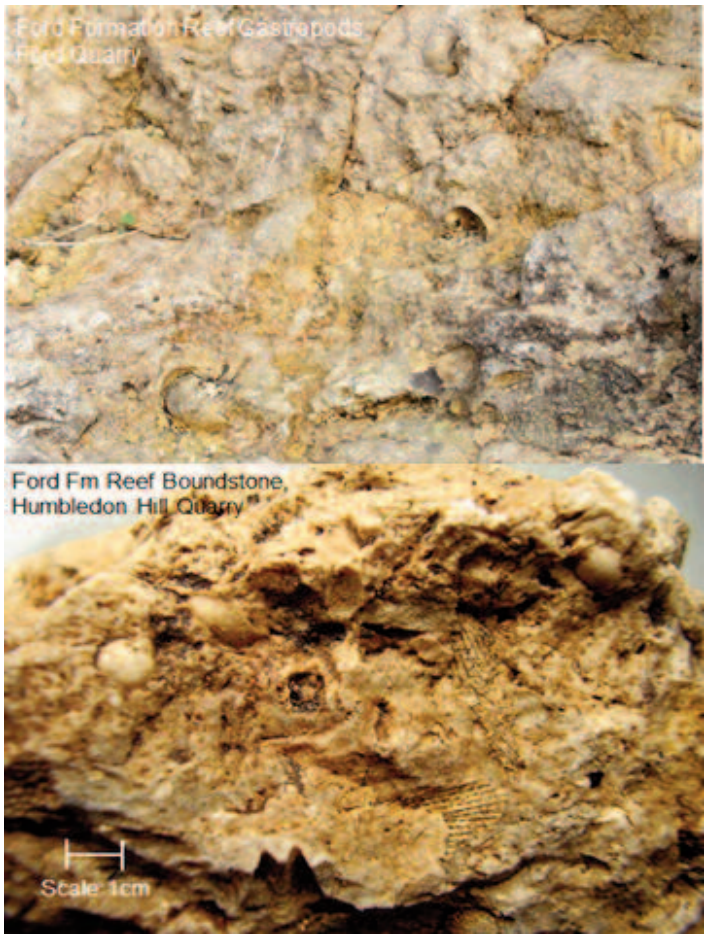


Figure 25 Boulder conglomerate of reef-rock blocks, Ford Formation, Blackhalls Rocks Foreshore

found at a similar stratigraphic position in the Permian Zechstein exposures in Germany and Poland. Trow Point is located east of the main Ford Formation reef, on the postulated deeper-water, seaward side, but the exact relationship between the Trow Point Bed and the reef has yet to be established.

In the upper part of the Ford Formation another localised facies development holds clues to the eventual fate of the reef. In places a boulder conglomerate rests on top of reef-facies strata and is composed of massive, jumbled blocks of reef material (up to 0.5m) surrounded by finer-grained ooidal grainstone dolomite and laminites. This is well exposed at the Hawthorn Quarry GCR site, and also on the foreshore at Blackhalls Rocks (Fig. 25), although at the latter locality the contact with the reef crest itself is not seen. This points to a period of significant erosion later in the reef's existence, suggesting a shallowing and possible emergence, probably linked to a fall in sea level. This is likely to have ultimately resulted in termination of reef growth. It is also notable that in the upper parts of the reef the fauna becomes more restricted, again pointing to possible emergence, and changes in climate and sea level, enabling greater evaporation and increase in water salinity.

Throughout the deposition of the Ford Formation sediment-loading and basin-slope instability continued, and it and underlying sedimented units continued to be affected by downslope gravity sliding. At Claxheugh Rock, both Ford Formation and underlying Raisby Formation olistoliths many tens of metres in size are exposed above significant slide planes (Fig. 26).

The balance between evaporation and water-replenishment in the Zechstein Sea is presumed to have shifted in favour of increased evaporative drawdown after the Ford Formation stage, because the next significant rock unit is an evaporite horizon. The Hartlepool Anhydrite Formation, EZ1b cycle, is not exposed onshore, but only recognised in off-shore boreholes, where it attains a maximum thickness of 130m. However, its former presence on-shore is indicated by the occurrence of a dissolution residue above Ford Formation strata in many places, particularly in more northerly parts of the outcrop.

At Trow Point a thin bed (150mm max.), representing the residue from the Hartlepool Anhydrite, appears as a brown clay horizon. This is all that remains of the Hartlepool Anhydrite after dissolution by circulating groundwaters, probably sometime about 60 million years ago in the Palaeocene. At this locality the overlying upper Magnesian Limestone strata are collapsed, broken and jumbled in a spectacular, discontinuous array, primarily as a result of foundering due to the dissolution of this anhydrite bed.

After deposition of the Hartlepool Anhydrite Formation Zechstein sea levels were restored and the second major cycle (EZ2, third sub-cycle) saw deposition of the dolomitic carbonate units of the Concretionary Limestone Formation and the Roker Dolomite Formation ('Upper Magnesian Limestone'). The nature of the sediments of these two formations is indicative of a depositional setting in a linked, shallow, marginal shelf and basin,

Figure 26 Ford Formation olistolith and slide-plane above Yellow Sands, Claxheugh, Sunderland.

downslope into a deeper-water environment. Recognising the lateral equivalence of these two previously separate formations, the term 'Roker Formation' is now common usage nomenclature for incorporating both these contiguous facies-units into one Formation unit.

The Roker Formation occupies the ground underlying the East Durham Plateau to the coast. While the outcrop is generally much less extensive than that of the Ford Formation, it does, however, form extensive coastal exposures southwards from South Shields. Near Seaham, the formation is generally *c.* 80–100m thick, while in off-shore boreholes its maximum recorded thickness is *c.* 200m.

The shallower-water 'Roker Dolomite' shelf facies (Fig. 27) is much less variable in character than the preceding Ford Formation, and is generally a buff to cream-coloured, well-bedded dolomite to dolomitic limestone with bedding on a scale of tens of centimetres, together with more thinly laminated pale dolomite horizons. Some of the more thinly laminated units are composed of fine dolomite particles, whereas the more thickly bedded horizons are coarser-grained dolomites. The more coarse-grained dolomite units are characteristically ooidal in texture and show cross-stratification (Fig. 28). These features are indicative of higher-energy deposition, and are consistent with a shallower, marginal shelf environment, albeit one close to the basin slope because debris slide units are also a feature of the Rocker dolomites. The more finely laminated dolomite mudstone horizons are recognised as sub-tidal units, and some show evidence of storm and sub-tidal channel deposition. In the coastal outcrops the shelf facies is developed in the Sunderland area around its type-locality at Roker (Fig. 27), and in the more southerly coastal areas south of Seaham.

In the southern area of outcrop a localised and unique facies of the Roker Formation developed. In the area around Hesleden

Figure 27 Cliffs of Roker Formation Dolomites — type-locality, Roker Park, Sunderland.

Dene and Blackhalls Rocks in south Co Durham, the Hesleden Dene Stromatolite Biostrome is exposed. It is a microbial-laminated, pale-cream-coloured dolomitic limestone composed of laminated microbialites, in its lower part (Fig. 29, *overleaf*), and huge columnar stromatolites in its upper parts (Fig. 30, *overleaf*). This unit occurs within a dolomitic limestone horizon *c.* 25m thick and overlies an erosion surface above the Ford Formation boulder conglomerate mentioned above. The stromatolites are in the form of large microbial domes up to 20m across and 3m high, which are spectacularly displayed on the shore at Blackhalls Rocks. Structures of this size are currently unique in the UK, and in marine Permian (Zechstein) strata generally. The stromatolite domes would have formed in shallow tidal waters, and are likely to reflect the reestablishment of lower-salinity waters after the evaporative EZ1b stage and re-establishment of an environment less hostile to life.

Figure 28 Roker Formation cross-stratified ooidal shelf grainstones, Roker Park, Sunderland.

Fine-grained laminated dolomites of the 'Concretionary Limestone' strata represent the equivalent basin-slope and deeper -water facies deposits of the Roker Formation. The presence of bituminous fish beds (Fulwell Fish Bed) occurring in parts of the formation suggest that this was an anoxic environment below wave base, in a stratified body of water. The basin slope instability that characterised earlier formations was still affecting EZ2 sedimentation, with horizons of debris slide units representing slope failures and mass downslope movement of already deposited material also occurring in this cycle. Sediment loading on the shelf edges was thus still evident, and this record of slope instability enabled the establishment of the depositional setting of a basin-margin slope.

Variability in bed thicknesses is recognised in the deeper-water facies, with some thinly bedded dolomites on a scale of tens of centimetres, and some very thinly laminated horizons of pale-cream, fine-grained dolomite mudstone. These latter beds tend to predominate at exposure.

Figure 29 Roker Formation microbial laminites, Blackhalls Rocks.

The correlation of these strata between sections is complicated by the absence of any notable marker-beds, although a reasonably consistent unit of thin-bedded, laminated dolomite known as the 'Flexible Limestone' — because of its mechanical properties — can be traced through some sections. However, the most notable feature of this unit is the presence of numerous spherical concretions, which occur at certain horizons, and have led to the local name of 'Cannon-Ball Limestone' for this bed. The concretions are spherical masses of calcite crystals, in a range of sizes, which are believed to have formed by later conversion of dolomite and growth of calcite crystals after the rock had been deposited (Braithwaite 1988). In some of the concretions, which are rarely up to 300–500mm across, the original bedding lamination can still be seen; in other concretions the later calcite growth has obliterated any primary bedding structure. When exposed in section, many of the concretions show radiating calcite spherulites, which are particularly well developed at Hendon beach and promenade, and inland at the Carley Hill Quarry complex on the outskirts of Sunderland (Fig. 31, *opposite*). The best exposures of the concretions themselves, however, are found at the 'Cannon-Ball Rocks' on Roker beach (Fig. 32, *opposite*), where they have been a tourist attraction since Victorian times. Later dissolution of dolomite around the concretions, and in the dolomite strata generally, has produced a number of interesting textures in the rock strata, appearing as 'nets' or 'coral-like'. These 'coralline or 'reticulate' dissolution patterns are well displayed in outcrops generally, and also in local building stones, particularly in and around the City of Sunderland.

Figure 30 Microbial domes, Hesleden Dene stromatolite biostrome, Roker Formation, Blackhalls Rocks.

Many of the Concretionary Limestone strata are fine-grained, with occasional horizons of harder recrystallised limestone where dolomite conversion has

taken place. These occur in prominent bands, usually between 100mm and 500mm thick. Some units also show areas of jumbled strata on a scale of tens of centimetres, being attributed to debris slides of unconsolidated and partly consolidated sediments off unstable submarine slopes. There is also more large-scale disruption to the strata in places, and foundering on a massive scale and collapse-brecciation as a result of dissolution of the underlying Hartlepool Anhydrite (*see* Fig. 11).

The carbonate sedimentation of the Roker Formation was terminated by an inferred fall in Zechstein sea level and return to hypersalinity since the next stratigraphic unit is the Fordon evaporite horizon at the top of the EZ2 cycle. The Fordon Formation is not represented as an evaporite horizon onshore, but in offshore boreholes is developed to *c.* 30m thickness of anhydrite beds. Onshore its dissolution residue is represented sporadically by a maximum of *c.* 10m of variable sediments, mainly clayey and dolomitic with limestone and anhydrite blocks. The residue is particularly well displayed in the cliffs at Seaham, where it appears in contorted layers (Fig. 33).

The final carbonate phase of Zechstein sedimentation is represented by the Seaham Formation, EZ3 cycle. The Seaham Formation, named from its type-locality in Seaham Harbour, is more restricted in extent than the preceding groups of Zechstein carbonates, occurring on-shore only in the vicinity of Seaham (Fig. 34, *overleaf*). As a whole, the formation shows much less lateral facies variations than any of the preceding Zechstein carbonate horizons and is also relatively uniform vertically. It reaches a maximum thickness of c. 30m, and is generally a thin-bedded, pale-buff-coloured dolomite to dolomitic limestone in its lower part, but containing less dolomite higher up the succession, where limestones are plentiful. Many of the thin-bedded units show preserved ripple structures, and cross-lamination is abundant, as is graded bedding indicative of a relatively moderate energy environment in relatively shallow water. At some horizons low in the succession significant cross-stratification and coarser grain size points to storm deposits.

The calcareous alga *Calcinema* is plentiful throughout much of the formation, but at certain horizons it takes on rock-forming proportions in the '*Calcinema* Beds'. Microbial laminites are also developed and occur higher up, near the top of the succession. Throughout much of the unit calcite concretions are developed, and are plentiful higher in the succession where dedolomitisation and replacement by calcite has converted many horizons to limestone packed with spherulites. At their maximum development the concretions attain a size of c. 200mm diameter, with complete loss of original sedimentary bedding observed in many places.

Like many of the preceding formations the Seaham Formation also shows brecciation and disruption of strata by foundering, due to the later dissolution of the underlying Fordon evaporite beds. These features are

Figure 31 Calcite spherulites, concretionary limestone facies of Roker Formation, Carley Hill Quarry, Sunderland.

Figure 32 Cannon-Ball Rocks, Roker — calcite concretions in concretionary limestone facies, Roker Formation.

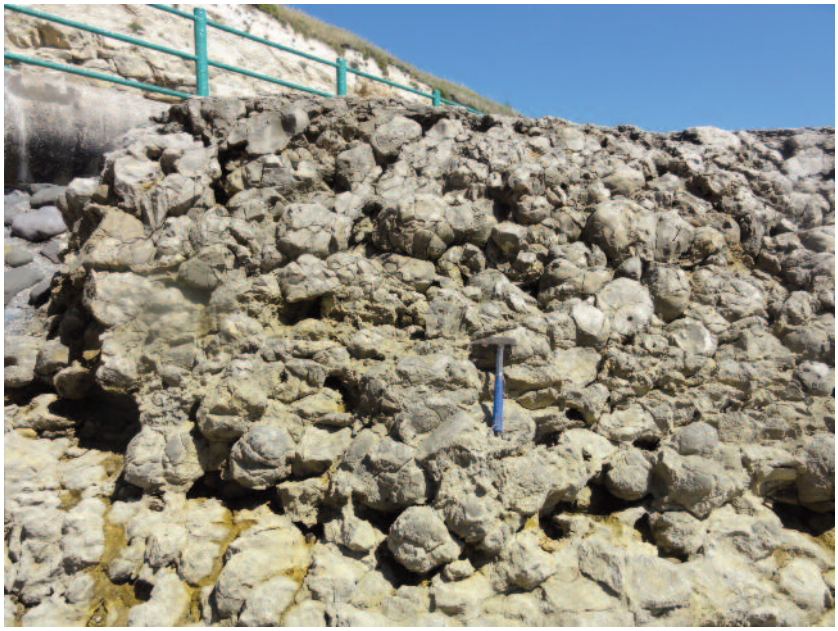


Figure 33 Seaham residue of the Fordon Evaporite, Fordon Formation, Seaham.

Figure 34 The Seaham Formation, Seaham Harbour.

particularly well developed in coastal sections in the Seaham area (Fig. 35, *opposite*).

The absence of major lateral variations in lithology that characterised the earlier Zechstein units, suggest that marked differences in the depth of the sea basin, or shelves around its edge were no longer exerting a significant control on sedimentation in the latest Permian. The absence of deep-water facies dolomitic mudstones and lack of extensive biota both point to a depositional setting as a large, stable, arid shelf area for the Seaham Formation. This suggests that by these later Permian times shelf margins had increased significantly, and that by now the deeper basinal areas of the Zechstein Sea lay farther eastwards, well beyond the present-day land area of Britain. This suggested increase in shelf area probably relates to lowering of Zechstein sea levels generally.

This inferred change in morphology of the basin and its margins is likely to have been a contributing factor in bringing to a close the major deposition of Zechstein carbonate sediments at the end of the Permian. Sediments above the Seaham Formation are no longer characterised by alternations of carbonates and evaporites, and only evaporites and marls are represented in the succession. Halite deposition also appears in the later evaporites, suggesting increasing hypersalinity, and points to progressive increases in drawdown and isolation of the basin. After the Seaham Formation, with lowering Zechstein sea levels and increasing hypersalinity, the depositional environment had thus evolved to one where evaporite deposition became favoured over carbonate production. Increasing Zechstein Basin isolation is likely to reflect global-scale Late Permian lowering of sea level, although tectonic modifications at the restricted interconnecting seaway with the open ocean may also have contributed.

Above the Seaham Formation the later Permian Billingham and Boulby Halites, Rotten Marl,and Sherburn Anhydrite EZ3/EZ4 strata are mainly evaporites and minor dolomitic marls. They are mainly developed offshore under the present-day North Sea basin. When studied as a group they give an interesting insight into the later development and palaeogeopgraphy of the Zechstein Basin.

The Billingham Anhydrite Formation is found onshore only in the area around Teesside and is developed to a maximum thickness of *c.* 8m. It is generally a dolomitic mudstone and laminated dolomite in its lowest parts with anhydrite — nodular in places — and with abundant microbial laminites in the upper parts. It is wholly a shallow-water deposit, with the laminites and anhydrite beds likely to have been formed in a sabkha setting on arid coastal plains, and represents a lowering of Zechstein sea level and a return to evaporative drawdown and hypersalinity after the Seaham Formation.

The succeeding Boulby Halite Formation is again only developed onshore in the Teesside area, but is well developed offshore, where boreholes show it to be *c.* 60m thick. It is mainly a coarse crystalline halite deposit with halitic dolomite in the lower parts, and is again believed to have formed on shallow coastal fringes in an extensive sabkha environment.

Figure 35 Contorted Seaham Formation strata resulting from dissolution of underlying Fordon Formation evaporite units — Cciffs north of Seaham Harbour, Seaham.

The Rotten Marl Formation is at a maximum of *c.* 10m thick, and is a silty mudstone with halite and gypsum crystals, the halite abundant generally. Again, it is only developed in the south of the area, and onshore appears to pass westwards into red sandstones.

The Sherburn Anhydrite Formation is again only found in the south of the area and is a dolomitic anhydrite *c.* 4m thick.

This group of sediments indicates that major changes in depositional conditions were occurring by the Late Permian, with the establishment of extensive shallow-water shelves and a sabkha environment under a generally hot, arid climate and hypersaline waters.

Sequence stratigraphy of Zechstein sediments

While the English Zechstein Cycles nomenclature (*see* Fig. 17) remains the standard terminology, it has also been appropriate to apply sequence stratigraphic analysis to the north-east England marine Permian succession (Tucker 1991). The traditional view of English Zechstein cyclicity has each cycle beginning with a carbonate unit and ending with an evaporite horizon. However, sequence stratigraphic analysis places the carbonate unit in the highstand systems tract (HST) and evaporite deposition as the lowstand systems tract (LST), with the sequence boundary (SB) at the start of the regressive phase heralding the onset of evaporite unit deposition as a lowstand wedge.

The first sequence, ZS1 (Fig. 36), has the Raisby carbonates deposited as a HST. The sequence boundary terminating the first sequence, ZS1, is placed at the start of the Raisby Downhill Slide breccias (*see* Fig. 35), with the Ford Formation EZ1b carbonates forming the TST and HST of ZS2. The sequence boundary for ZS2 is placed at the regressive stage of Ford reef erosion, giving the boulder conglomerates, followed by the lowstand deposition

Figure 36 Sequence stratigraphy of the Zechstein carbonate-evaporite succession of north-east England (based in part on data from Tucker 1991).

Formation	Systems Tract or Surface	Sequence
Seaham Formation	TST/HST	ZS4
Fordon Evaporites	Major Regression, start LST, ZS4	ZS4
Roker Formation	TST/HST ZS3	ZS3
Hartlepool Anhydrite	Major Regression at Start, LST ZS3	ZS3
Ford Formation	TST/HST, ZS2, SB at top	ZS2
Raisby Downhill Slide	Forced Regression, SB above ZS1 at top of breccias	ZS1
Raisby Formation	TST/HST	ZS1
Marl Slate Formation	TST	ZS1

ZECHSTEIN :SEQUENCE STRATIGRAPHY

of the Hartlepool Anhydrite of the classic EZ1b cycle. Hence in sequence stratigraphic terms each cycle *starts* with an evaporite unit in contrast to the traditional cycle definition which starts with a carbonate unit.

However, in studies of Zechstein successions from the North German Basin alternative interpretations are possible. Strohmenger and co-workers (1996) identify karstic erosion surfaces *within* the ZC1 carbonates (Raisby equivalents), indicating an erosive sequence boundary, with overlying carbonates representing the next cycle *as lowstand and TST deposits*, with the maximum flooding surface placed at the top of their ZC1 carbonate deposition and overlying evaporites occurring as the HST.

This apparent contradiction emphasises the difficulties, firstly, in attempting to apply sequence stratigraphic models developed for marine systems to carbonate-evaporite successions generally, which often have significant magnitude changes of relative sea level. Secondly, it emphasises the difficulties in attempting to apply the approach to different locations within a basin and its margins, which have different localised sedimentary successions and are only poorly comparable. More work is needed before a full and meaningful sequence stratigraphic analysis can be applied to Zechstein carbonate-evaporite successions generally.

Epilogue

Studies of the onshore marine Permian deposits of north-east England enable us to reconstruct the morphology, and understand the development and evolution of the western margins of the Zechstein Permian basin.

Evidence from the British sections complements and expands that derived from German and Polish sections of the basin, and lead to a much more comprehensive understanding of the dynamics and evolution of the basin as a whole. This in turn enables us to better understand the tectonic and sedimentological evolution and development of the northern sub-polar regions of the Pangaean supercontinent itself.

The recognition of favourable geological structure in the Permian deposits under the North Sea, coupled with the discovery of oil in east Yorkshire, prompted the search for offshore oil. In 1965 gas was discovered in the southern North Sea Basin, and a year later the West Sole platform went into production. Thus began the exploitation of North Sea oil and gas fields, driven by our increasing understanding of north-east England marine Permian geology.

A study of the UK marine Permian sections has also provided a better understanding of the nature of the oil and gas provinces across the southern Permian basin in general, and has greatly assisted in the search for hydrocarbon reserves across the whole of the North Sea Basin. The technological developments introduced initially for North Sea exploration and production are now used worldwide. The onshore marine Permian sections of north-east England now form an international focus for petroleum industry training, education and research, attracting participants on a worldwide basis. And recent investigations have now identified new petroleum source rocks within the Permian succession and potential new targets for future development. It might only be a tiny corner of north-east England, but it certainly now has global significance!

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The North Pennines Orefield: a major regional phase of mantle sourced mineralisation, magmatism and transtension during the earliest Permian

Eddie Dempsey

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[OUGS Newcastle Symposium: Pangaea: Life and Times; original transcription by Maggie Deytrikh from the Symposium recording; edited by Dr Dempsey and POUGS Editor David M. Jones.]

Introduction

Basically my title means, 'The North Pennines Orefield, it's not what we thought it was'. For anyone who is not familiar with it, The North Pennines Orefield is situated in this part of Northern England *[pointed out on a PowerPoint slide — Ed.]*, standing out fairly well on a topographic map and a regular road map. The Alston Block is bounded by the A66 to the South and by the A69 to the north, and within this area sits our North Pennines Orefield. To the north of The Alston Block is the Stublick Fault, which as you come out towards the coast, turns into the Ninety Fathom Fault; and to the south, you have the Lunedale Fault, which turns into the Butterknowle Fault. To the west of the Alston Block is the Pennine Escarpment, with the Pennine faults. The Alston Block itself is largely composed of Carboniferous rocks, and although this symposium is about the Permian, I am going to spend most of my time in the Carboniferous, Period — but trust me I'll get there with the Permian!

In addition to all of the Carboniferous rocks, we do have these yellow ones here — the Whin Sill *[pointed out on a PowerPoint slide — Ed.]*, which will become important as we go on through this talk. Stratigraphically we are dealing with Carboniferous and we are largely in limestones and sandstones, and some muds. Where the veins of The North Pennines Orefield are best expressed, is where there are good thick limestones, as these make really good wall rocks, which break open easily so that you get one big clean fracture through it, and nice thick veins. Where it is a bit more muddy, the deformation becomes a bit more diffuse and veins do not form quite as well.

Specifically, these are the Upper Limestone and the Middle Limestone — particularly the Three-Yard Limestone, the Six-Fathom Hazle and The Great Limestone. When you drive through the North Pennines, The Great Limestone is the outcrop that you will see again and again, and it is one of the best limestones to mine as well.

Early research

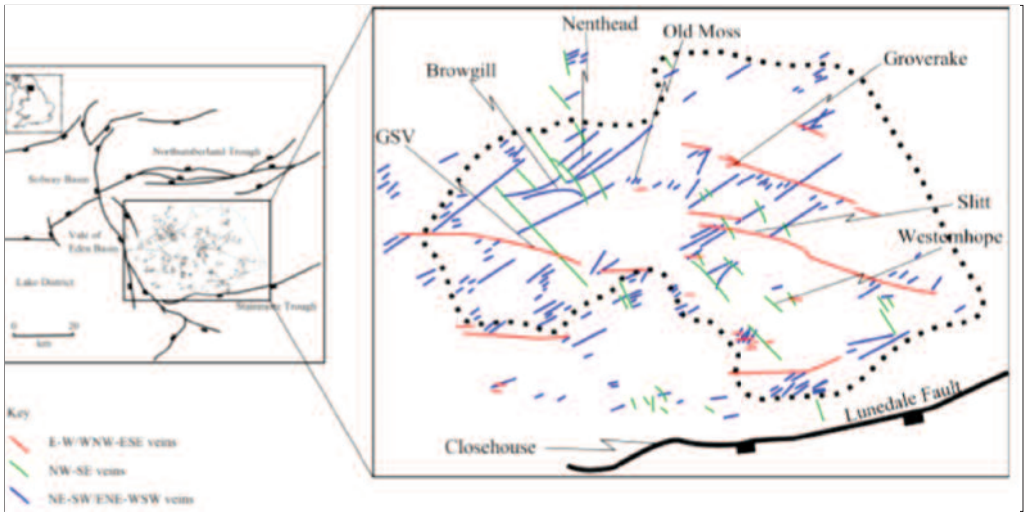
The North Pennine Block is fault-bounded. Why it became fault-bounded was a matter of controversy for a long time, as geologists could not understand why it had positive structural highs. So, there were several theories proposed, involving normal rifting with horsts and grabens; but once geologists did some geophysical surveys, they found an anomaly underneath, which was the Weardale granite. The Weardale granite does not actually outcrop anywhere, and it was only through these geophysical surveys that geologists figured out that it was there, and that it lies underneath the Alston Block. Up to this point in fieldwork nobody really knew why the orefield was there, then the granite was discovered underneath and everyone went 'Bingo! Granite intrusion underneath, lots of ores came up, sorted! I wonder what the granite looks like, let's drill a bore hole.' They drilled down into it, and they found that the limestones were sitting unconformably on top of the granite. The granite was not intruded. The granite turned out to be a Caledonian granite, which had been uplifted and eroded before any limestones had been deposited on it. So, therefore the mineral veins that are in the limestones cannot be related to the formation of this granite. So that put the cat among the pigeons for a little while!

But others kept looking at it, and could see that there is this purple zone in the ore field *[pointed out on a PowerPoint slide — Ed.]*. That's the outer limit of the fluorite zone. Outside this, there is a lot of barite, with the green line representing the inner limit of the barite zone. There is some overlap and in some places there are gaps, but the fluorite zone is very much centred on the granite. So people really thought that the granite has to have something to do with this, which has been our thinking for a long time.

We can see this stratigraphy in Figure 1. The red lines represent our mineral veins. It is not just broad mineralisation, it is focused in veins, and that is quite important. We have three distinct sets of veins, three different colours: red, green and blue. Red veins run east–west; they are generally the longest and biggest veins in the system. In addition, we have north-west to south-east veins — green; and east-north-east to west-south-west veins — blue. It is quite a complex story.

Part of trying to understand the origin of this stratigraphy is to examine the veins and to try to date the material; the North Pennines was a big area for lead mining, and thus uranium-lead and lead dating was the obvious option. Many people have attempted such dating, and have achieved dates of 280 +/-30mya and of 250–150mya. A lot of the dates are around the 200mya mark, so no real agreement whatsoever.

Figure 1 Mineral veins of the North Pennine Orefield, based upon Dunham 1990.



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Cann and Banks (2001) reckon that there were two different pulses of mineralisation, one *c.* 250mya and then a much bigger one at *c.* 210mya.

Looking at the granites

However, many thought that this interpretation was not quite good enough. We wanted to know why the veins are there. Why they sit over a granite; and the dating does not really mean anything, as when there is that much of a spread, it is hard to trust them.

People continued to analyse the data and have come up with several different hypotheses of the geological histories of the area. One of the most widely accepted is that of Johnson and Dunham (2001) — that during the Carboniferous there was extensive deformation and extension forming our northern English big basins. Then at the start of the Permian the Whin Sill was emplaced, with some compression. A few million years after the Whin Sill emplacement the mineral veins were emplaced, over quite a large time period (anything up to 100 million years), a long time for what is not that big an orefield to form.

Looking back to the granites, if you have ever been up to the ore field, you will have seen this model up on the bill boards (Fig. 2). Geologists have been thinking that the granite has to have something to do with the emplacement of the orefield. So they looked at the fluids inside fluorite and calcite. They found that these fluids were quite similar to Zechstein seawater and to Zechstein sediments. What we reckon is happening is that the granite is still quite warm through radioactive decay; the granite has kept its heat and has caused what is called a 'chimney effect'. Any water in it is rising up, sucking water in from the sides, where we have large sedimentary basins on either side of the granite. The granite is sucking water from the sides and bringing it up (*see* Fig. 2), along with any minerals in it to deposit them above the granite when the liquid cools down. This model fits in with there being some type of Mississippi Valley deposit, in which fluids flowing through sediments leach out the metals in the sediments and redeposit them somewhere else in the sediment. Anytime you see someone showing you this diagram now, I want you to tell them it's wrong! I'm going to show you.

So, we need to look at the mineralisation. This is my favourite hand specimen from the North Pennines *[shown in a PowerPoint slide — Ed.]*. It sums up the North Pennines in one small rock: it has fluorite, galena, pyrite, quartz, a mixture of chalco-pyrite and haematite, and some more fluorite.

Figure 2 Artists' impression of 'Chimney Effect' explanation of North Pennines mineralisation.

Figure 3 Representative hand specimen with a mixture of quartz, calcite, galena and pyrite.

All of the mineralisation is vein-hosted, so if you look on the BGS Digi-map website, you can look at all the mineral veins and you get nice linear vein sets parallel to the main structures in the area. If you go back to Kingsley Dunham's early work, he showed that the mineralisation is all at these veins, but also that there are some 'flats', where some sediments have been altered and mineralised. If you look at Dunham's maps, these flat mineralisations are always adjacent to the veins. So, what is happening is that the fluids are coming up along the faults, forming veins, and every so often, spreading out into the adjacent rocks. So we get some replacement of the rocks, and some enrichment of things like iron, particularly, ironstone. When we mine them we want to focus on the veins themselves, because there are fewer contaminants in them, and you do nit have to pick out all the calcite and sand and things like that.

There are nice clear galena veins, choc-a-block with quartz. These ones are a mixture of quartz, calcite, galena and pyrite (Fig. 3). As you can see, they have quite complex fracture networks. It is not a case of just saying 'that's the orientation of our faults and our fractures, and this is what happened.' It is more complex — a bit of a mess!

So, when we're looking at our minerals, we know that they're sitting over the Alston Block, they're in the veins. We really want to focus upon which minerals. We want to focus upon when the minerals got there, but more importantly, why did the minerals get there?

So, have quartz, fluorites carbonates, a metalliferous sulphide and our metalliferous supergene minerals. Metalliferous sulphides include everything from galena, lead, chalcopyrite to copper and iron, pyrite, marcasite, even some pyhrrotite (magnetic pyrite). We also want to see if there is any consistency in the age relationship. Is there a pattern to the mineralisation? Were there some minerals that came in first, then another, then another, in a consistent sequence Not really. They all seem to be fairly coeval, mostly coming in at the same time, apart from the sulphides, brownish-gold in colour. Sulphides always seem to be the earliest stage of mineralisation in the veins, and the final mineralisation was the supergene metals — but much later than the current processes, when metals move around. The fluorite is often in the last dregs of mineralisation. This is why we wanted to focus on the sulphides, which were there when the metal mineralisations began. So, when did it start.

Re-examining the dating

We have seen that a wide range of dates have been determined from radiometric dating. So, if you go to Cann and Banks work (2001), they say that the main phase of mineralisation was from 250 million years on. To do that, they looked at fluorites in particular, and at barites. They wanted to know what fluids were inside these minerals. What information does that tell us about the age and the origin of these minerals? When we look at a typical fluorite crystal we can see that there are a lot of fluid trails.

The main technique for analysing these is crush-leach extraction. Basically, you crush up the rock, wash out whatever fluids are in it, and analyse them. But this process is indiscriminate. The crystal will have multiple phases, initial growth zones when the mineral was first grown and where the fluid was included in it. Afterwards, the rocks were fractured, several times and in many orientations. There are also little healed fractures with fluid inclusions on those. Thus, if you crush the rock indiscriminately you get fluids from all of those different sources; you get fluids from the original growth, but also fluids from the time when the fracturing happened. We do not know if all the fracturing happened at one time; some fractures could have occurred as mush as 100 million years apart. However, we cannot know because we have mixed all the fluids together; and therefore you get something approaching an average, which really does not tell you anything.

We also found that there is much evidence for remobilisation and replacement of these ore bodies. You can see what would have been originally cubes of fluorite, which are now replaced by quartz and chalcedony *[shown in a PowerPoint slide of a thin section — Ed.]*. So, by analysing the fluid inclusions after the process described above, you do not know whether you are looking at the initial fluids or the fluids that have caused this later remobilisation and replacement. There is a good chance that what you are looking at is that later event, that your initial fluids are going to be so washed out and gone, that you are not really going to see them anymore. So, the research that Cann and Banks published may not have been the origin of the North Pennines Orefield, it may have been a subsequent event. Current research at Durham University suggests that this event is more to do with the barite mineralisation around it, rather than the initiation of the ore zone itself.

Sulphides are the key

Copper and iron sulphides contain two isotopes: rhenium and osmium. The only way that these isotopes can go into pyrite is during formation and once they are in the pyrite, they are locked in. During remobilisation, nothing happens — the rhenium and osmium stay the same. If found, rhenium and osmium are commonly chalcophilic, siderophilic and organophilic elements. So the pyrite is a chalcopyrite, and if we had any bitumen from the same source, we could analyse it in the same way, but unfortunately there is none.

Rhenium and osmium are intrinsic to the isotopic composition of the mineralising fluids. What I really mean by this statement is that when a pyrite crystal forms, once it crystallises, it takes on an identical isotopic composition to that of the fluid that it came from — and that composition will be recorded and will not change through the evolution of that orefield.

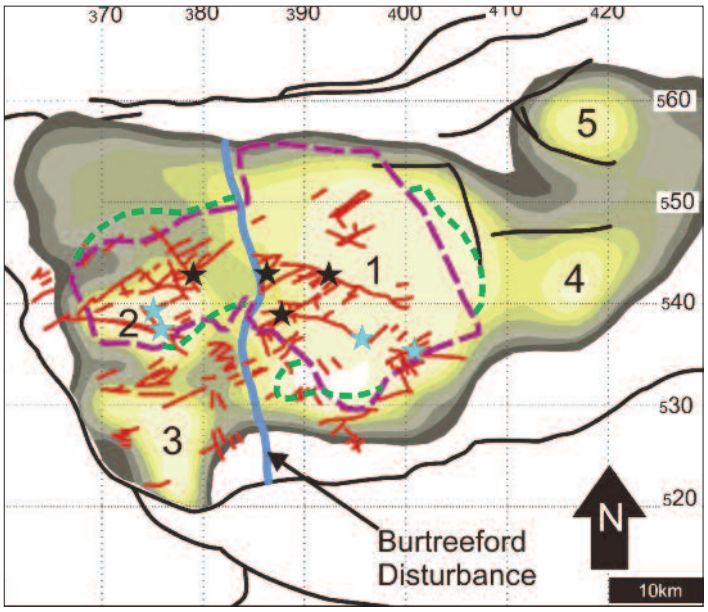
The other important aspect is that we can date it. Rhenium decays into osmium and we can do fairly simple mathematics to derive the age by measuring the absolute quantities of osmium isotopes and rhenium isotopes; so we did (Fig. 4). We collected a lot of samples and analysed any that had enough rhenium and osmium in them. The concentrations that we were dealing with, for rhenium, we were down to *c*. 1–3 parts per billion. For the osmium, we were down to 10 parts per trillion. To get an age from concentrations that low was a bit of a 'miracle', but we did get an age out, and it has quite a high uncertainty — of 37 million years — which is purely down to the low concentrations. There is nothing we can do about that. The age we got is 308mya.

We also calculated the initial osmium composition. The osmium composition in the fluids that formed these pyrites is a bit uncertain. There is a ratio of different isotopes of *c*. 0.2 +/- 0.1, a bit of a 'wishy-washy' result, but we looked at each sample and worked out an average. We could see we had two clear outliers that just did not fit with everything else, so we re-ran the analysis with the two outliers removed, assuming that there was something wrong with them. *[Showing figures in a PowerPoint diagram slide — Ed.]* This figure here of '3.7' is high — we want that number to be below '1'. Anything below 1 for the MSWD (Mean Square Weighted Deviation) indicates that it is natural scatter. Anything above 1 is really telling you that there is something wrong, that there is something causing scatter.

As we thought that these results were being caused by the two outlying samples, we re-ran the analysis, but got basically the same age; however, the uncertainty value was less — down to an error of 20 million years. And our initial osmium ratio is a lot more refined. So, now we have a value of 0.15 +/- 0.01, a number we think we can trust, because our MSWD is within an acceptable range.

Then we looked again at the initial osmium and decided that we could probably divide this into two groups, one with a very low initial osmium and one with a slightly higher one. When we calculated these ages we ended up with ages of 295mya and 294mya +/-30–40Ma. Once again, this represents a high uncertainty because of the low concentrations. What is important about these ages, however, trying to understand why the uncertainty is there?

Figure 4 Initial osmium ratios; the black stars represent samples with the low initial osmium and the blue stars represent the slightly higher initial osmium ratios.



Reviewing the graphs again, we find the initial osmium value at 0.15. Any fluids that come from the mantle have very low initial osmium ratios and we have calculated that our fluids should be about 295mya +/- 30Ma. What mantle source could there be at that time that could be related to these sulphides? There was only one option — the Whin Sill, which has been dated fairly accurately at 297mya. We therefore collected some samples of the Whin Sill and analysed them for their initial osmium composition, and it came out bang on the exact same result. So the red line (which also represents the Mantle) on the Figure 5 diagram is our average Whin Sill composition; and the dashed black line on the graph are the sulphides from the North Pennines Orefield. We regard this as a bit of a 'smoking gun'. As said, we have two groups: one group that is basically spot-on mantle source, spot on the Whin Sill; and a second group that is a bit higher. When we look at the two groups spatially, the low value ones (black stars on Fig. 4) and the higher value ones (blue stars on Fig. 4) group separately.

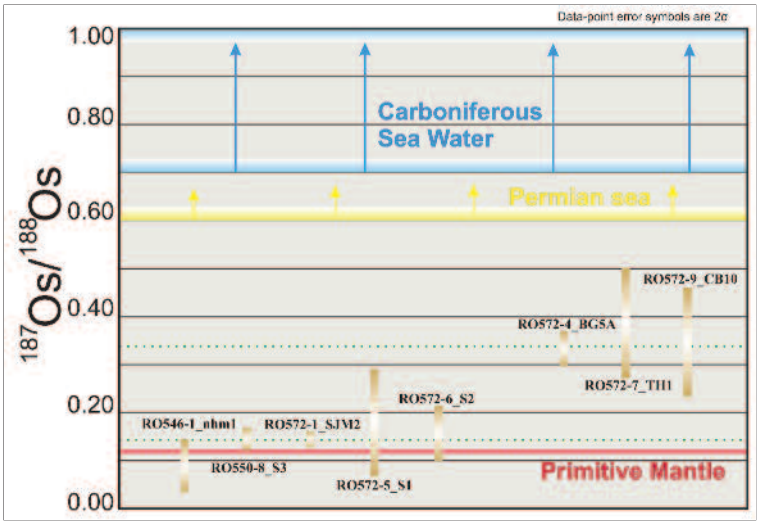
So, we suggest the thick blue, north–south line on Figure 4 is the Burtreeford disturbance, which is a large east-facing monocline that cuts right through the orefield. That is the fluid conduit — the fault line where the ores come up, and from there spread into all the other veins and fractures in the orefield. That is why it is here that we get the purest mantle signature. But as the veins and fractures spread east and west they have started to react with the sediments, picking up a slight signature from them.

If the metals from the North Pennines Orefield were derived from the surrounding sediments they would retain the same initial osmium values as those sediments. If the metals were sourced from the Zechstein brines we would see an iOs ratio of *c.* 0.6 and if they were sourced from the carboniferous sediments in the basins adjacent to the Alston Block they would have an even higher iOs ratio of 0.7 or higher (*see* Fig. 5).

There is no way that the metals in the North Pennine Orefield have come from leaching the sediments, because of the hot granite lying beneath it. The only way that the orefield could have mineralised these metals is if they come from a mantle source — and the only mantle source available at that time is the Whin Sill.

So, I am not saying that our metals are actually coming out of the Whin Sill itself, but that the process that led to the Whin Sill being intruded was the same process that let the hot fluids — the hot metalliferous brines — come up from the mantle and start mineralising.

Figure 5 Osmium isotopes fluids weighted averages.



Again, the red line Figure 5 is the Whin Sill and there are our two group averages. So, why are there these intrusions of large igneous bodies at this time? Why this extensive mineralisation? We come back to the structural side of things. As we saw, all the mineralisation is associated with veins, it is not an overall replacement; rather, it is structurally controlled. It was time to get out and do some proper, traditional structural geology. We measured strikes and dips, and as many lineations as possible. We plotted them all and then did some palaeo-stress analysis to find out what was going on at this time.

Our palaeo-stress analysis produced this nice diagram Fig. 6, *opposite*), with an east–west compression and a north–south extension. And such compression and extension agree with what many people had said earlier about the structure in the area.

We also did some Mohr's circle analysis. In a plot of this analysis, each dot *[shown in a PowerPoint slide graph — Ed.]* represents one of our faults or one of our veins. The closer you are to this area *[pointed out on the PowerPoint slide — Ed.]* in this stress field, the more likely you are to fail. So it is quite clear that one group was 'unhappy' with that stress field. Back in the lab we reanalysed this group separately, and it turned out that the north-west–south-east veins, which in the field were regularly cross-cut by every other structure, were likely to be older. Indeed when we did the stress analysis on the north-west–south-east group of veins we got a completely different stress field. We found that these veins had north–south compression, and east–west extension. These tectonics fit in perfectly with Variscan-age shortening at that time.

So, at the very end of the Carboniferous Period, this area should have been undergoing north–south shortening. The early structures and faults record this. The bulk of the mineralisation was on every other structure. When we looked at that, we had north-south extension, but east-west compression.

The whole tectonic framework has shifted at this point in time. The rocks were squeezed and squeezed, and then suddenly extension began. These processes created the stress field at the end of the Carboniferous.

Permian melting

And finally to the Permian, and the start of the extension. As extension began, so too did all of the mineralisation, and the magmatism.

This structural story fits in with all the work that has been done around the northern England on the structural history of these troughs and highs. Work by Nic De Paola and colleagues (De Paola *et al*. 2005) shows that at some point after the Variscan there occurred a phase of transtension — strike-slip with an extensional component. De Paola was unable to put a date on this extension, but he shows that it had to have been after the Variscan, and it affected the whole area.

The same story is recorded by Underhill *et al.* (1988) in their study of the Dent Line just to the south of the Alston Block, forming the western edge of the Askrigg Block. The story is clearly regional at this time, and we have finally been able to date the switch from compression to extension through the mineralisation of the North Pennines.

Nic De Paola's, however, shows that all of these tectonics were controlled by the structures and that their orientation east-north-east–west-south-west shows them to be Caledonian structures. So, were back to the underlying granite again.

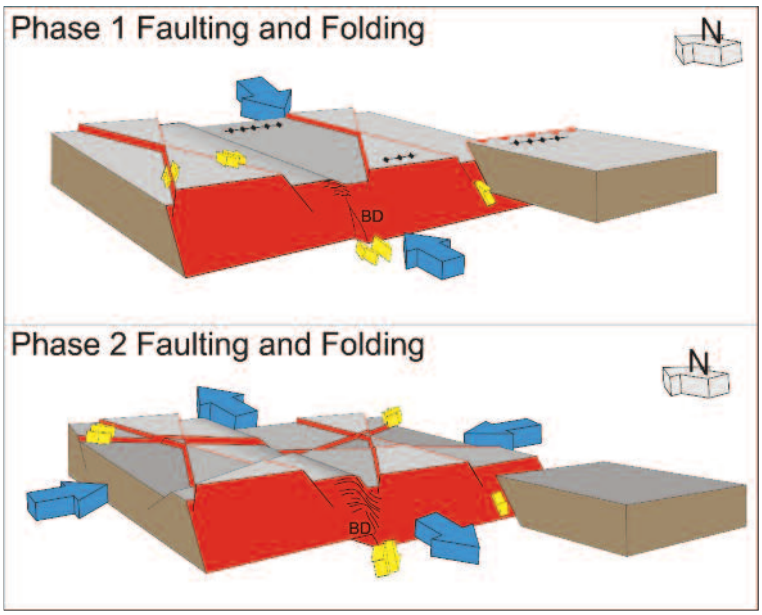


Figure 6 Phase model of faulting and folding of the Pennines Block.

The granite was not the controlling factor here, the tectonics that actually led to the granite emplacement — those Caledonian tectonics were still influential in the Permian because all of the faults that propagated through the orefield and other coastal sections *[many of which were visited on Symposium field trips — Ed.]* were controlled by the deep-rooted Caledonian structures that are buried underneath.

So, while the granite is not important, the process that led to the granite is. The Caledonian lineament was in place, and the North Pennine Orefield was superimposed on the granite and defined by it. This interpretation fits perfectly with the models put forward by Nic De Paola *et al.* (2005) So, what was really going on at this time? Stepping right back to the Caledonian, compression was taking place, mashing and sliding the rocks along large sinistral strike-slip faults and continuing into the Carboniferous, with some back-arc extension, but overall continued compression After something like 100Ma of compression, suddenly, in the Permian, the tectonic processes in the crust 'relaxed' with decompressional melting. After such continuous compression, melting began. The rocks in the whole of northern Europe started to melt, from the Oslo Graben into Scotland and down into northern England, creating the Whin Sill. There was decompressional melting, and because of this melting the Mantle was able to up-well into the area, heating the rocks and causing extra hot briny fluids to develop, creating the North Pennines Orefield.

Concluding remarks

To recap, the North Pennines Orefield is structurally controlled. It formed at the time of the significant switch point between north–south compression and north–south extension. The mineralisation that occurred *c.* 295mya — the Whin Sill magmatism (not the Whin Sill itself) — is the key to the North Pennines Orefield. Structures that are associated with the Weardale Granite still control and influence the orefield, but this granite is too old and too cold. Rather, the orefield metals are coming from the Whin Sill Permain magmatism.

So, the Permian in Northern England, didn't exactly kick off with a bang, but with a fizz.

Acknowledgement

Dr Dempsey would like to acknowledge and thank his colleagues for their help in the research reported in this article:

R. E. Holdsworth, D. Selby, C. LeCornu and B. Young.

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Book review

Harlow, Dilys 2014 *The Land of the Beacons Way: Scenery and geology across the Brecon Beacons National Park*. Geologists Association, South Wales Group (ISBN 978-0-90322-202-0; paperback, 128pp; £7.95)

The Brecon Beacons have always been quite a special place for me and were the place where, quite by coincidence, I became interested in geology. I was taking a mountaineering assessment there and we were all given a mountainous subject to research over the course of an evening, to be turned into a five-minute talk 'on the hill' the following day. I was given 'the geology of the Brecon Beacons', and I never looked back!

If I'd had this guide to hand back then, I might not have needed to spend quite so much time researching. After a brief introduction to geology, about 20 pages are devoted to 'The Big Picture', giving a geological overview of the area form the Cambrian right up to the effects of recent landslips. I often find introductory sections are either much too short, giving too little detail, or too long, losing the weekend visitor in masses of detail, but here just the right amount of information is presented with clear diagrams and illustrative photographs.

The meat of the book is the descriptions of the geology along the Beacons Way, a 152km (94.5 mile) walking route that crosses the Brecon Beacons from east to west (as presented here) and normally completed in eight days. The geology follows the route closely and is divided into chapters that correspond to each day, the intention being that this is a companion volume to more general walking routes and maps. To an extent, this is a mistake, because the book cannot stand alone in any sense. You couldn't spend a couple of days in the area and use this book to plan any geological walks without also having to take at least an OS map. Some basic information is missing, such as the length of each walking day and public transport options for those wanting to return to base at the end of each day.

This is a minor complaint, though, and missing practical details are more than made up for by the geological detail. You can be pretty sure that any time you cross from one bedrock to another it will be mentioned in the text, and geological features at all scales are described, photographed and illustrated so that you can't miss them. Dilys Harlow's writing style is compact but comprehensive and engaging and it's a good guide even for the armchair reader. Each day has 10 pages or so devoted to it; I haven't used this book in the field, but can easily imagine how it would enrich a walk.

If you are visiting the Brecon Beacons and planning on doing any walking, I heartily recommend this book. You'll need other sources to plan the walks, but this really is a treasure trove of geological information, and for most visitors it contains everything you need to know.

— Rich Blagden, BSc Hons (Open) Nat Sci (Earth Sciences)

Book review

Richardson, Alan 2015 *A Pocket Guide to Geological Field Recording*. Alan Richardson (no ISBN given — this is a web / print-on-demand publication; paperback, iv + 40pp; £4.99)

As the author says — this book is a quick reference guide with bare essentials, and assumes that the reader has already studied geological theory. Thirty-nine numbered pages may seem very brief, but the book is packed with information, much of it diagrammatic.

The back cover illustrates sedimentary grain size and sorting; and there are convenient centimetre scales on each long edge.

After the introduction comes a summary of method, then the code of conduct and lists of essential equipment. There is an extremely useful section on the correct way to use a compass clinometer and a separate compass.

The first main section, on igneous rocks, has separate sections on recording and classifying, including texture, colour and minerals.

The sedimentary section suggests the use of dilute hydrochloric acid (0.1M solution).

Grain size is used as a main starting point for classification, through numbered sections with multiple diagrams.

Sedimentary structures are illustrated, together with a table of graphic log, fossils and mapping symbols.

The metamorphic section is short but comprehensive, and is followed by a section on folds, faults and cleavage.

This slim A5-format booklet is just right for the pocket or rucksack and the list of contents helps as an index for quick reference in the field.

— Rosemary Darby, BA (Open), BSc Hons (Open), Certs Ed: UK & NZ

Zechstein carbonates as a petroleum reservoir, Argyll/Ardmore Field, UK Continental Shelf

Jon Gluyas

Thalia © 2015

Introduction

The UK's first offshore oil production began in June 1975 from the Argyll Field. In a 17-year period the field produced 72.6 million barrels of sweet, light crude. In 1992 production from the field became uneconomic, the field was abandoned, all wells were plugged and the facilities removed.

Ten years later in January 2002 two new oil companies, Tuscan Energy, and Acorn Oil and Gas were awarded the licence to redevelop the Argyll Field — renamed Ardmore. The first Ardmore well was drilled in the summer of 2003 and 'second' oil flowed in September 2003. However, this second phase of production from the field lasted only two years before the field was abandoned for a second time. Although the redevelopment of the field proved to be a technical success the two start-up companies were under-capitalised and as a consequence were unable to fund continued development drilling.

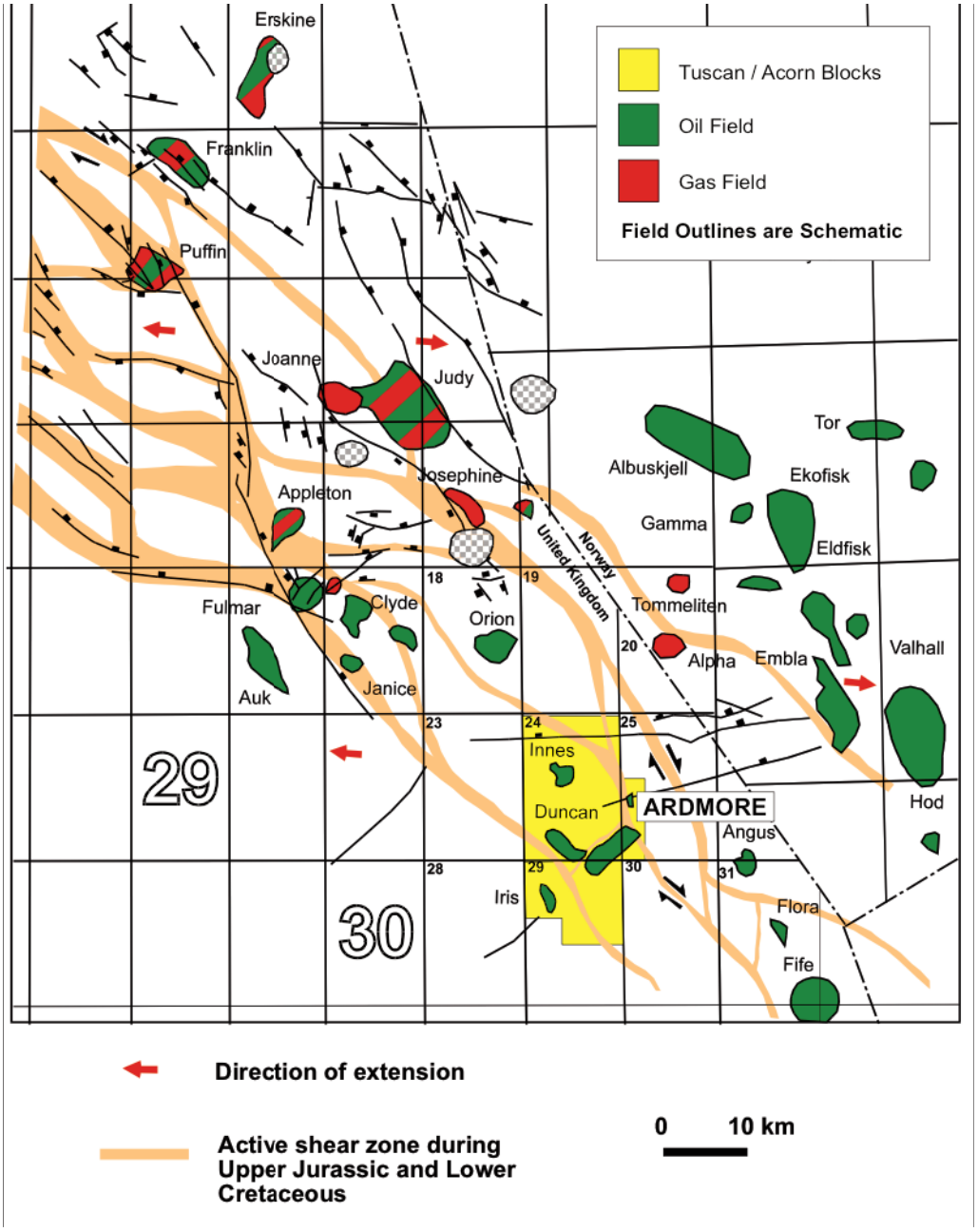
This case history compares the original Argyll production phase and the later Ardmore production interval and examines the viability of oil field redevelopment.

Location and history

The Ardmore/Argyll Field is located in a large tilted fault block in an elevated position on the western edge of the Central Graben of the North Sea High (Fig. 1). Argyll was discovered in 1969 with well 30/24-1 by Hamilton Brothers and partners. However, this well was not initially recognised to be an oil discovery and it was abandoned. As a consequence 30/24-2 was drilled close to the first well. It tested at 4,314bopd (barrels of oil per day) from Permian Zechstein carbonates. The same well also flowed 1,446bopd from a deeper sandstone reservoir, believed at the time to be the Rotliegend (therefore Permian in age), but later proved as Devonian. Appraisal followed and in June 1975 the Argyll Field became the first oil field on stream on the UK continental shelf (Pennington 1975).

A converted drill-ship the *Transworld 58* was used as the production vessel and crude oil was transhipped via offshore loading. Initially the field produced light, sweet oil at high rate. However, it was clear from the outset that the geology of the Argyll Field was complex. Most of the early production came from wells that were completed in vuggy Permian, Zechstein carbonates. The deeper, oil-bearing sandstones though described as Rotliegend were unlike those seen in the Southern North Sea Gas Basin and onshore England. Not until several years after field start up were these red beds beneath the Zechstein recognised to be a combination of Permian Rotliegend sandstones and Devonian (Old Red) sandstones and siltstones (Heward *et al.* 2003). The difficulty of distinguishing between two, barren, red-bed sequences was not the only geological problem to be addressed. Small quantities of oil were found in a later well (30/24-6) in shallow marine Jurassic sandstones, which only

Figure 1 Location map of the Argyll/Ardmore and adjacent fields and showing the license acreage of Acorn and Tuscan in 2003.



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occur on the western flank of the field. Further surprises were encountered. In the north-east of the field the Zechstein reservoir is completely eroded and Upper Cretaceous Chalk seals variably fractured but otherwise tight Devonian sandstones that were proven productive by well 30/25a-2 (1982, tested at 2,280bopd) but never completed as a producer. Core from 30/24-20 (1982) revealed a conglomerate facies of Upper Jurassic age containing pebbles of Zechstein dolomite and oil-bearing matrix that had not been described previously. Even the final well drilled by Hamilton on the southern edge of the field (30/24-39, 1989) delivered a further puzzle when volcanic rock (probably lowermost Permian Karl Formation) was encountered at the level where Rotliegend sandstones were expected.

Production peaked just one year after field start-up in 1976 (Fig. 2) with a half-year average of *c.* 28,000bopd. At this time only the Zechstein interval was on production Rotliegend and Devonian interval completions were added in 1979 and 1982, respectively, giving two lesser peaks in production of just over 20,000bopd in the first halves of 1979 and 1982.

A second field, Duncan, was brought on stream in Block 30/24 in 1984. The Duncan Field (*see* Fig. 1) with a Jurassic Fulmar sandstone reservoir began production and in so doing the combined output from the two fields surpassed 27,000bopd as a half-yearly average. In 1985 the Innes Field began production from a Rotliegend sandstone reservoir where total production reached 33,000bopd in the first half of 1985. As the Innes crude had a significantly higher gas–oil ratio than that from Argyll or Duncan it was possible to install gas lift on the Argyll wells, thereby extending field life. However, production from all three fields continued to decline and by 1992 the rate was 6,000bopd ,which was limited by the 70% field water cut and the fluid handling capacity of the production vessel that was then on station (20,000bfpd [barrels of fluid per day]). All three fields were abandoned in 1992.

Structure and stratigraphy

Block 30/24 is at the southern end of the Central Graben and north of the Mid-North Sea High. It lies largely on the rift shoulder straddling the major bounding fault to the southernmost part of the Central Graben and above a significant transfer zone. It is likely that movement on this system has caused repeated inversions of the fault block that contains Ardmore leading to the complex, residual stratigraphy seen in the area with multiple and composite unconformities (Fig. 3, *opposite*). The most recent inversion appears to have occurred in the early Neogene, giving Ardmore its characteristic elongate NE–SW trap geometry (Fig. 4, *opposite*).

The main stratigraphic intervals are described below.

Devonian

The oldest rocks penetrated in the area of the Ardmore Field are Devonian, Kyle Group limestones, informally referred to as the 'Mid Devonian Limestone'. The reservoir section in the Ardmore Field occurs within the Buchan Formation of the Upper Old Red Group, a thick succession of continental red-beds that overlie the limestone.

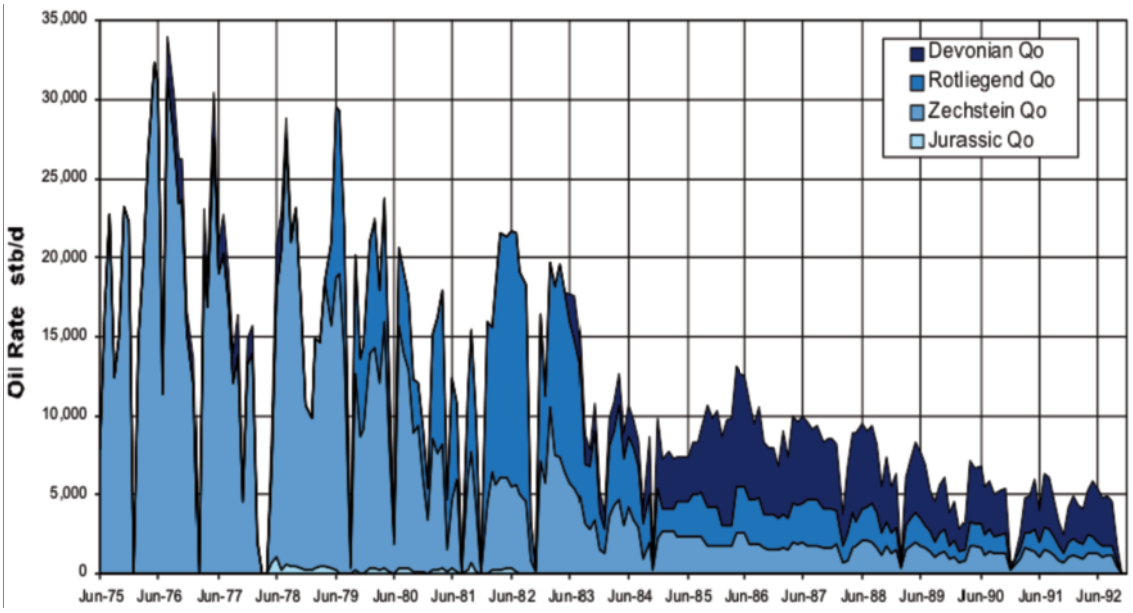
The Devonian dips at 7–10° to the south-west such that the oldest rock penetrated is in the north-east corner of the Ardmore Field while progressively younger Devonian sub-crops the base Permian Unconformity to the south-west (Fig 5, *page 42*). It is possible that the Devonian interval contains subtle angular unconformities and considerable missing section although unequivocal evidence of such is lacking.

Permian — Rotliegend and Zechstein

Above what can confidently be identified as Devonian sandstones, well 30/24-10 in the north of Ardmore, contains what has been described as weathered olivine basalt beneath 30m of white sandstone. In the south-west of the field 30/24-39 includes weathered volcanics or volcaniclastics beneath the Zechstein carbonates. Both intervals may be lowermost Permian Karl Formation.

Late Permian, Rotliegend, Auk Formation sandstone overlies the Devonian. Rotliegend sandstones in Ardmore are confined to a low relief NW–SE syn-depositional valley through the centre of the field (Robson 1991; *see* Fig. 4). These sandstones are typical Rotliegend aeolian and non-fluvial, water-laid facies. Beyond the immediate area of the Ardmore Field, the Rotliegend sandstones are widespread and thicker with a greater range of facies (including fluvial sandstones).

Figure 2 Production history for the four reservoir intervals in the Argyll/Ardmore Field. The Jurassic reservoir is minor.



The Kupferschiefer mudstone and Zechstein carbonates overstep the Rotliegend sandstones and rest directly upon the Devonian strata (*see* Fig. 5). Halibut Bank Formation carbonates overlie the Kupferschiefer and are in turn overlain by the Sapropelic Dolomite and Turbot Bank Formation carbonates.

The original fabric of the Halibut and Turbot formations is difficult due to pervasive dolomitisation. The Halibut Bank interval has a transitional

boundary with the Kupferschiefer. It comprises friable and argillaceous dolomite interlaminated on a centimetre scale with non-porous dolomite. This is overlain by an upward-coarsening, poorly sorted, clast supported dolomite breccia.

The Halibut Bank Formation passes transitionally upwards into the basal unit of Turbot Bank Formation (Sapropelic Dolomite). It is a laminated dolomitic argillaceous mudstone with thin (mm-scale) graded dolomitised beds.

The Turbot Formation passes transitionally upwards from the laminated carbonate slope facies at the top of the Sapropelic Dolomite into a meso- to finely crystalline dolomite with possible biomoulds.

Upper Jurassic Humber Group

The best development of Upper Jurassic Fulmar sandstones occurs in a N–S strip, across the centre of the field. Here it only poorly developed as a combination of basal breccia with pebbles of Zechstein dolomite overlain by clean quartzose sandstone. On the western flank of Ardmore the shallow marine, Fulmar sandstone is better developed. Well 30/24-6 produced about a 0.4 million barrels of oil from this interval.

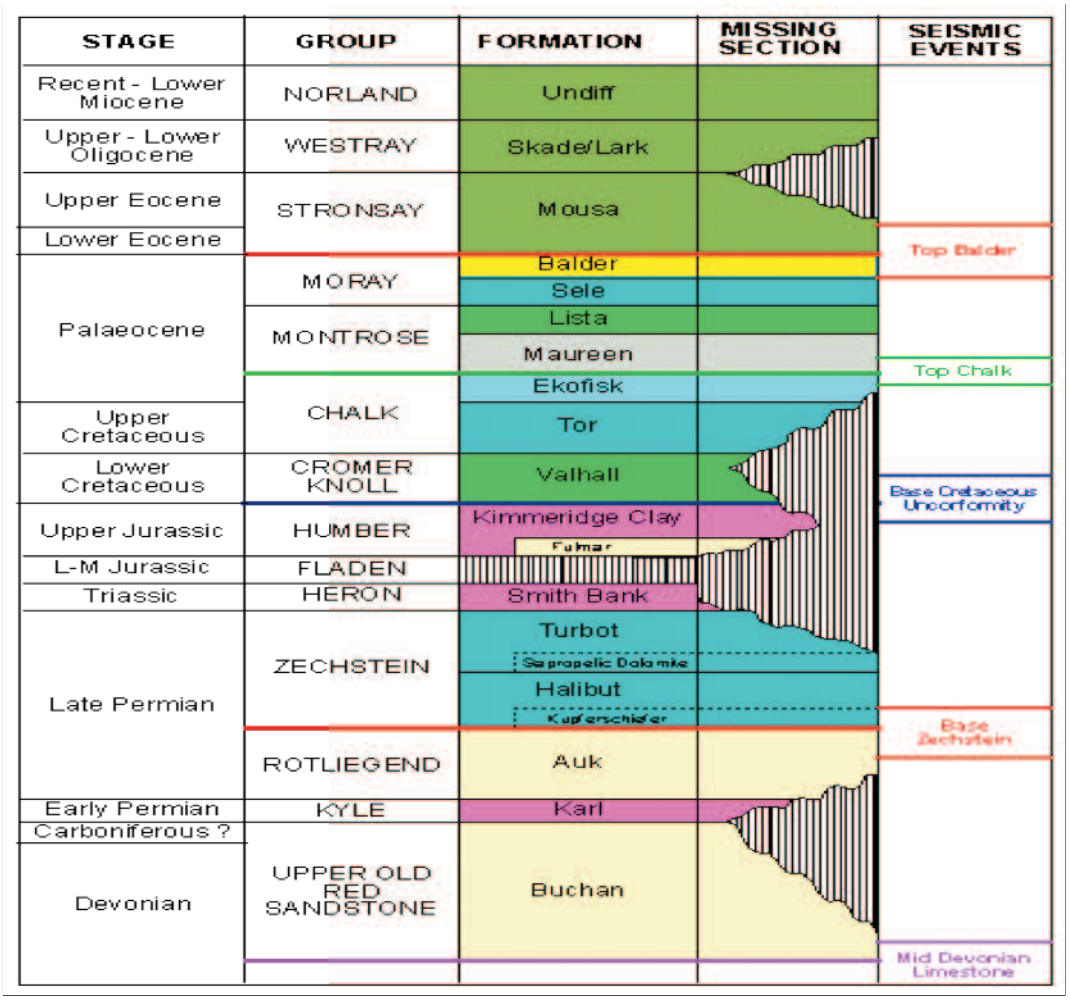


Figure 3 Stratigraphy of the Argyll/Ardmore Field. The multiple unconformities that occur both within the reservoir intervals and in the overburden demonstrate the frequency of tectonic activity in the area.

Upper Cretaceous — Palaeocene Chalk Group

The Chalk is present across the whole of greater Ardmore area, indicating that by Upper Cretaceous times the area was finally submerged. Oil shows occur throughout much of this sequence around Ardmore, although the same interval acts as the ultimate top seal to the north-eastern corner of the field.

Palaeocene/Eocene — Recent Stronsay, Westray and Nordland Groups

The Tertiary section that overlies Ardmore is largely argillaceous and it is not considered to be prospective.

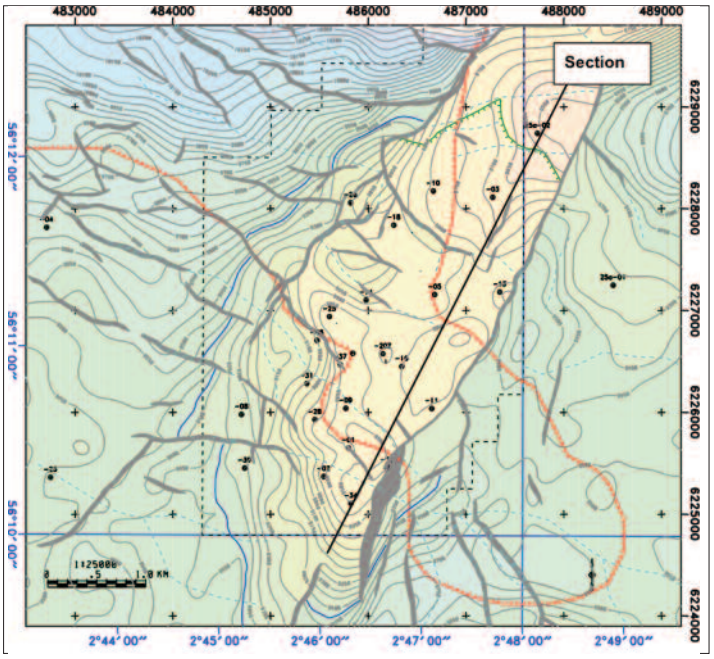
Reservoirs

Ardmore contains four reservoir units (Devonian, Rotliegend, Zechstein and Jurassic, *see* Fig. 3). The three oldest are in pressure and fluid communication and the fourth, youngest and minor unit (Jurassic) is independent.

Upper Devonian

The oil-bearing section of the Buchan Formation contains sandstones and siltstones with subordinate mudstones, conglomerates and rare coaly mudstones. The log trends and core exhibit a cyclicity of sandstone and finer sediments for the whole of the

Figure 4 Map of the Ardmore Field (2003-vintage and based on interpretation of 3D seismic data). The blue contour line is the oil–water contact and the area within the red, hatched line bounds the distribution of Permian Rotliegend reservoir.



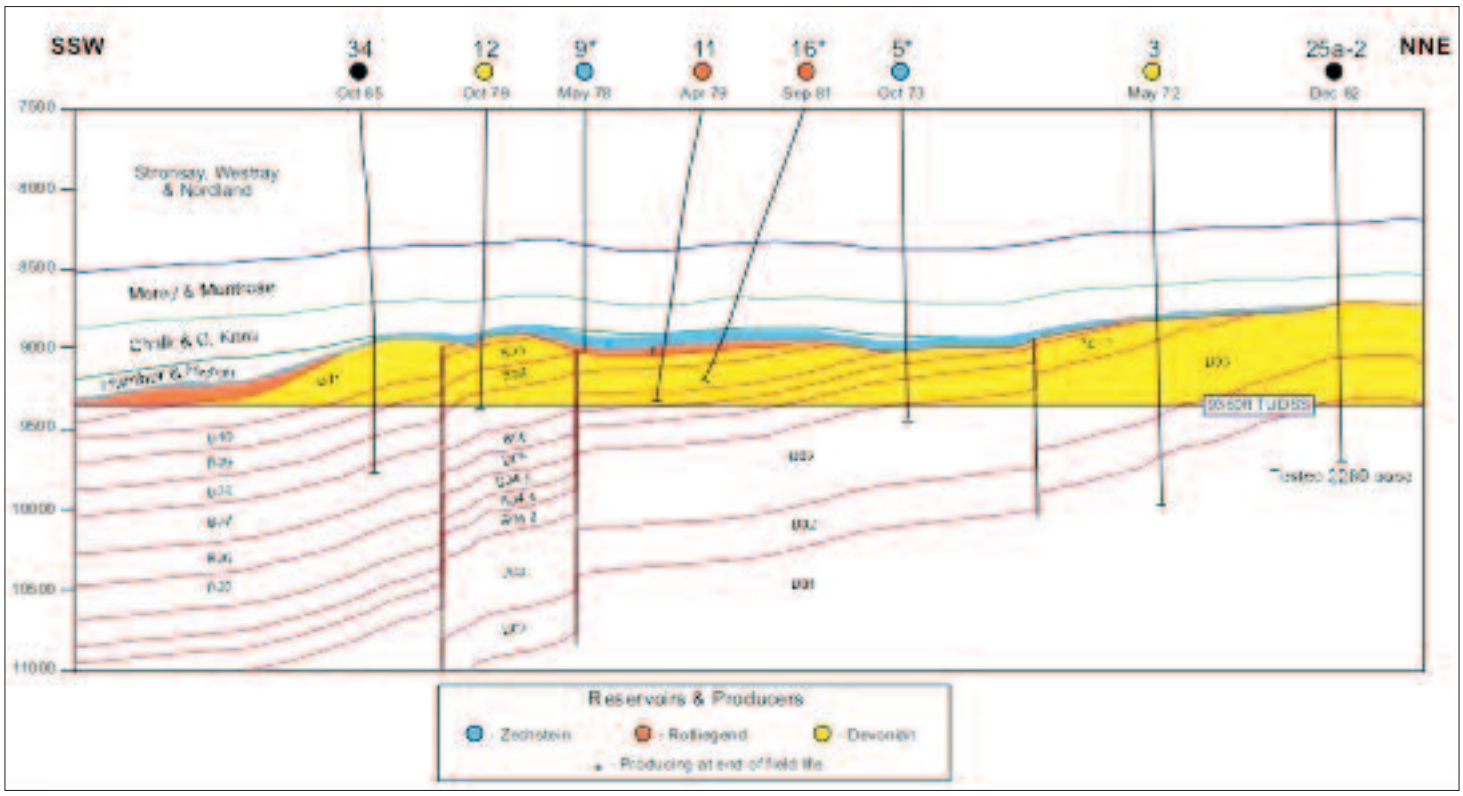


Figure 5 SW–NE section through the Argyll/Ardmore Field showing multiple unconformities in the reservoir and overburden intervals (line of section shown on Fig. 4). The internal stratigraphy of the Devonian interval is also illustrated.

interval, but there is also a clear overall upward trend to cleaner better sorted sandstones interbedded with mudstones from a rather homogenous and monotonous collection of silty sandstones and sandy siltstones at the base. The Buchan Formation is been divided into intervals interpreted to have been deposited in either arid or humid environments and then wells are correlated using the humid to arid cyclicity (*see* Fig. 5).

The ranges in porosity and permeability for the sandstones within the Devonian section are large, from 5–28% and <1mD to >1D respectively.

Rotliegend

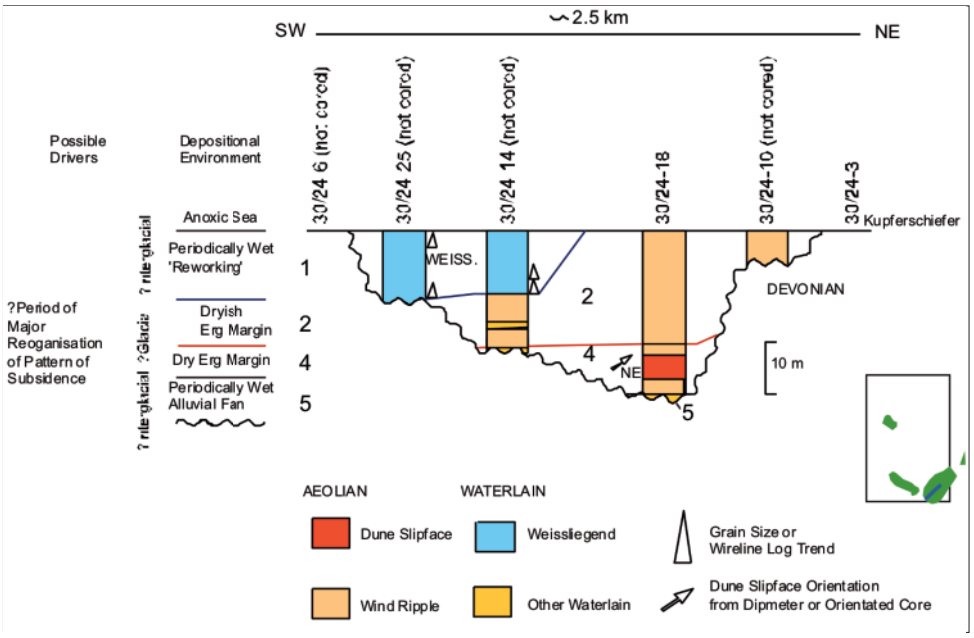
Five reservoir zones consist of different proportions of four main facies associations, which infill topography and onlap the Argyll high of the Rotliegend Auk Formation of Ardmore (Fig. 6; Heward *et al.* 2003). The four facies associations include:

- aeolian slipface sandstones;
- aeolian, ripple-laminated sandstones;
- water-laid sandstones; and
- water-laid conglomerates and breccias.

The most permeable reservoirs within the Rotliegend are the coarse water-laid sandstones (Weissliegend) that dominate Unit 1. The most porous reservoirs are the medium-grained dune slipface sandstones, most abundant in Unit 3. Units 2 and 4, dominated by wind ripple-laminated sands, are relatively tight and have characteristically high-water saturations. Permeability in the water-laid sandstones of Unit 1 and aeolian sandstones is high, typically 1-5D.

Production logs run during the completion of Argyll wells 30/24-11 and Innes well 30/24-24 confirm that the bulk of production was from Unit 1. Seven wells produced oil from the Rotliegend reservoir in Argyll. However, material balance estimates indicate that the Auk Formation was not just an oil producer. It alone among the reservoirs of Argyll has a substantial aquifer. Aquifer size has been calculated to be *c.* 10 billion barrels based both on the material balance calculations and also

Figure 6 Distribution of lithofacies within the Rotliegend of the Argyll/Ardmore Field, SW–NE cross-section.



from pressure data gathered from exploration wells drilled to the north and west of Argyll after production began.

Zechstein

The Zechstein reservoir comprises a dual porosity system of large pores visible to the naked eye and micropores measured during core analysis. The large-scale macro pores visible in core comprise fractures and vugs. Some of the fractures are of tectonic origin, but most comprises anastomosing fracture systems within collapse breccias (Fig. 7). Vugs include irregular 100μm to 5mm diameter pores formed by dissolution of allochems during dolomitisation and evaporite dissolution. Some vugs also formed by non-fabric selective dissolution.

Core plug measurements from the Zechstein reservoir are few because much of the core is fragmented. In consequence the data may be biased towards the poorer-quality reservoir. The highest porosities have been measured in the collapse breccias, which have both intercrystalline and mesovuggy porosity. These have porosities of up to 20% and permeability up to 1D, although permeability and porosity are poorly correlated. Indeed, many plugs have only *c.* 5% porosity, while permeability values measured in hundreds of millidarcies have been recorded. The cause of the high permeability at low porosity is fracturing. This appears to be natural and not core induced.

Given the difficulty of quantifying the reservoir quality of the Zechstein from the existing conventional core analysis data, supplementary information has been gathered from the drilling reports. Mud losses were common during drilling of the karstic layers in both the Turbot and Halibut Formations with reported rates ranging from 60–200 barrels per minute. The effects of this mud invasion are readily seen in both fractures and vugs within the core. Drilling of the Zechstein was also typified by erratic drilling breaks and frequent jamming of the core barrel.

Upper Jurassic

The Upper Jurassic Fulmar Formation reservoir is poorly developed on the west flank of Ardmore, where it comprises fine- to medium-grained clean to argillaceous sandstones. Net to gross is typically high (80–100%) and porosity in the range 16–21%. Permeability varies widely from a few millidarcies in the more argillaceous intervals to a few hundred millidarcies in the cleanest sandstones.

Source

The Upper Jurassic Kimmeridge Clay Formation is the source rock for oil within each of the three fields on Block 30/24.

STOIIP (stock tank oil initially-in-place) and reserves

Initial oil in place and reserves has been calculated many times for Ardmore and its predecessor Argyll since the field was discovered in 1969. More than 10 sets of STOIIP calculations from internal company records between 1985 and 2003 have been collated. These range from 200 to 430MMstb (million stock tank barrels) for the four reservoirs combined. A significant uncertainty affecting gross rock volume is the depth of the initial oil water contact. There are few penetrations of a proper contact, with the most common value being *c.* 9360ft TVDSS (true vertical depth sub-sea) as seen in the central and south-western parts of the field. Projection of a deeper contact (9430ft TVDSS) on a field-wide basis certainly accounts for most of the additional oil in the highest STOIIP figure, with most increase occurring in the Devonian reservoir. In the north-eastern part of the field the quality of the Devonian reservoir diminishes and in most instances only 'oil down to' depths that have been measured.

The P_{50} STOIIP estimate is 375MMstb (summed means). The subdivision by reservoir gives 33MMStb in the Jurassic, 42MMstb in the Zechstein, 50MMstb in the Rotliegend and 250MMstbl in the Devonian.

The Argyll Field produced 72.6MMstb with 41.1MMstb from the Zechstein reservoir, 18.2MMstb from the Rotliegend reservoir and 12.8MMstb from the Devonian reservoir. The Fulmar sandstone produced *c.* 0.4MMstb from one well. Comparison of STOIIP and produced reserves appears to indicate that recovery factor for the Zechstein was almost 100% and *c.* 37% for the Rotliegend, while only 5% of the in-place volume of Devonian oil recovered. Clearly the recovery factor for the Zechstein is unreasonable. It is known from the pressure data that the Zechstein, Rotliegend and Devonian reservoirs are in pressure communication and therefore it is concluded that some of the oil produced from the Zechstein was originally reservoired in either the Rotliegend or Devonian.

Figure 7 Collapse breccia in Zechstein carbonates, Durham coast, UK. Note vuggy porosity and fractures. These rocks are comparable to the Zechstein reservoir in the Argyll/Ardmore Field.

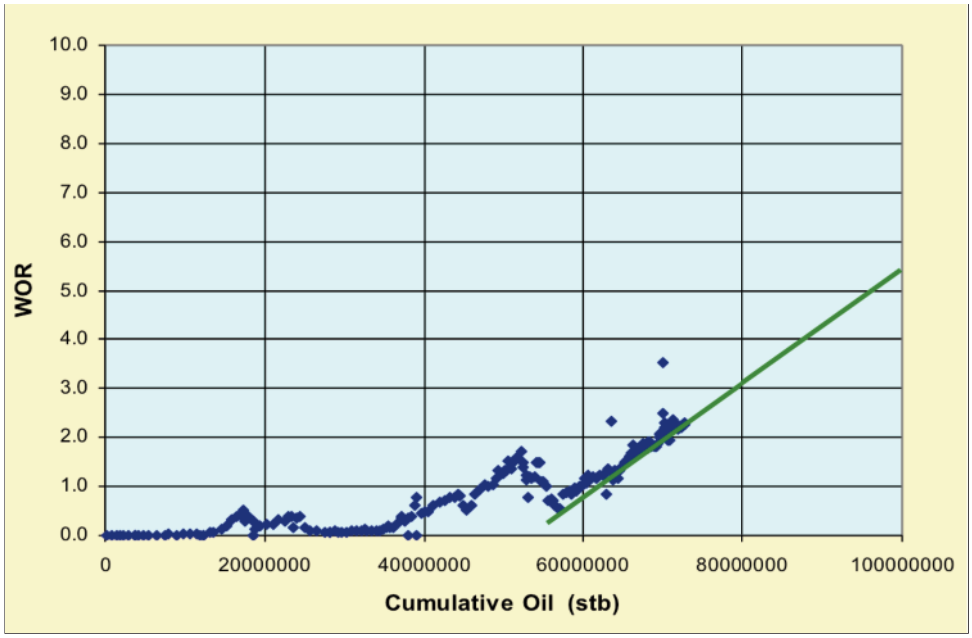


Figure 8 Extrapolation of the water:oil ratio at Ardmore.

The remaining reserves for Ardmore have been calculated both by extrapolating the water-cut trend for the Ardmore Field and by modelling the reservoir. Both methods give similar results. When Argyll was abandoned it was producing *c.* 6,000bopd. The total daily fluid rate was 20,000bfpd, a figure constrained by the production facility then available. Thus at abandonment the water:oil ratio was *c.* 2, and extrapolation of the water:oil ratio to 5 (Fig. 8) yields a remaining oil reserve of about 25MMstb.

Ardmore development and production

For the Ardmore development, three firm and one contingent wells were planned for the first phase of field redevelopment to access the remaining 25MMstb of oil reserves. A further three sub-surface locations were identified as possible future well locations dependent upon the outcome of initial drilling and production. By the time the field was abandoned for a second time three new wells had been drilled and two of these new wells were sidetracked.

Two types of target were identified for the Ardmore wells. The low risk targets are Devonian reservoired oil, proven during the Argyll phase but never produced. The reservoir quality is variable from poor to good and well rates were expected to be modest relative to the rate that could be achieved from Rotliegend and Zechstein completions. The most likely initial water-cut in such wells is zero.

The higher-risk targets were the Zechstein and Rotliegend reservoirs, where because of their excellent properties unconstrained well rates could exceed 20,000bopd. The prediction of the initial water-cut in such wells and the rate at which water-cut would increase was the major risk.

Oil production from Ardmore was not as expected, although it took some while to understand that this was not owing to errors in the reservoir description, but rather failure to execute drilling and completions as planned. This error was compounded by problems with the production facility, which was unable to meet the design criterion and handle 50,000bwpd.

The first well drilled for the Ardmore production phase (30/24-T1) was located updip of one of the best wells from the Argyll production period (30/24-9). Tuscan and Acorn had the benefit of being able to place the well on the basis of interpreted 3D seismic data, while only a sparse 2D data set was available to Hamilton. T1 was expected to penetrate Zechstein carbonates lying above Devonian sandstones. It was anticipated that flushed horizons could occur anywhere in the section, although on the basis of the old wells it was thought probable that the base of the Zechstein, or top of the Devonian — which was coincident with the top perforations in the old well near by — would be the most likely flushed section.

Given the limited funds available to the two companies, it was deemed necessary to produce the well at the highest rate possible, that is, from the combined Zechstein and Devonian. It was recognised that water ingress to the Zechstein was likely to be rapid and to this end a complex completion strategy was employed. A sliding sleeve was used as part of the completion over the Zechstein interval. The idea was that water could be shut off from Zechstein leaving only the Devonian producing.

Well 30/24-T1 was drilled in August 2003. Petrophysical analysis revealed a full oil column. No water was encountered. The Zechstein was high quality as was the underlying uppermost Devonian. Pressure data indicated that the field had recovered about two-thirds of the way between the virgin pressure and the field abandonment pressure. All looked good.

In October 2003 production began. The choke was progressively opened and under natural flow the rate increased to more than 20,000bopd — miracle. The rate was c. 30% higher than any previous well had ever managed during the Argyll production phase. A production rate in excess of 20,000bopd was maintained for two months without resort to switching on the electro-submersible pump. During these two months a second well T2 was drilled in the mid-part of the field. Petrophysical analysis of this well indicated that some intervals were water-flushed and in line with prognosis an initial water:oil ratio of c. 1 was anticipated. Preparation was made to bring T2 on stream. However, in the days just before T2 came on, BS&W (base solids and water) in T1 began to rise from near zero to a few percent. Clearly water breakthrough had begun to occur. T2 came on stream and despite a 50% water-cut the field production rose to 28,000bopd — just for one day. Then the unexpected happened. Although the production equipment had been designed to handle 50,000bwpd it could not handle a total fluid of 20,000bpd — disaster. Day after day the water:oil ratio increased and day after day the production system tripped. Efforts to reduce the water-cut by closing the sliding sleeve failed. Could water be flowing through the Devonian at such high rate?

Two problems with production kit were eventually identified and remedial work was begun to correct the equipment, which had not been built to specification. However, it took about six months before the production system could handle the 50,000bwpd as designed, and an enormous quantity of oil production had been lost.

The problem with T1 remained and as water-cut increased, so oil production decreased. By late 2003 the field was producing only 5,000bopd and at that rate it was failing to return sufficient revenue to pay of the loans made to the two companies. Problems with the flow multimeter also meant that it was not possible to be confident about the relative proportions of oil and water production from the two wells. In the meantime, T3 was being drilled.

Eventually the decision was made to work over T1 and try to shut off the water. In doing so the source of the water was revealed. It was coming from the Zechstein, but an error in placing the sliding sleeve meant that even when in the closed position it was covering the perforated interval. Moreover, it was also discovered that the Devonian section was completely filled with lost circulation material. It had not produced a barrel of oil. The Devonian interval was cleaned and the Zechstein section blanked-off. When the well was brought back into production it flowed at 11,000bopd from the Devonian alone; a rate three times better than had ever been seen from the Devonian during the Argyll production period — miracle.

Had well 30/24-T1 been drilled and completed correctly it would have produced more than 30,000bopd and history would have been different. However, the damage was done and despite a further well and two sidetracks being drilled the field was little more than breaking even. The two companies had insufficient funds to drill their way out of the problem. By mid-2005 Tuscan ceased trading, leaving Acorn to limp on. Acorn did raise sufficient funds to continue, but in an environment of rapidly rising oil price and consequential hike in day-rates for contractors, contracts were terminated. Acorn oversaw the abandonment of the three wells and closed the second chapter in the Argyll/Ardmore production history. Ardmore produced about five million barrels.

Conclusions

Two small companies with very limited resources brought the abandoned Argyll Field back to life as the Ardmore Field. At first, oil was achieved in less than two years from the acquisition of the licence. The limited resources meant that there was no margin for error with the development. However, there were errors and despite those being small relative to many other field start-ups, the two small companies were unable to continue to produce the field. Ardmore was not a commercial success, although the production proved beyond doubt that there are *c.* 20mmbbl remaining, which for a properly capitalised company should make an attractive development.

Postscript

In December 2010 the area containing the Ardmore Field was relicensed; this time to a far more financially robust company, Enquest plc. Their plans for a second redevelopment of the Ardmore Field contain, for the first time, water injection and pressure support. The field, renamed for a second time and now called Alma, came on stream on October 28th 2015.

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Book review

Simpson, Morven, and Broadhurst, Fred; del Strother, Peter and Rhodes, Jennifer (rev) 2014 *A Building Stones Guide to Central Manchester* (3rd edn). Manchester Geological Association / PJDS Consulting Ltd (ISBN 978-0-99287-131-4; paperback, 67pp; £9.95 [£4.50 to members of the Manchester Geological Association])

This A5 size booklet provides a much welcome update to this publication, which first appeared in 1975. Produced by the Manchester Geological Association, the revisers have taken advantage of full colour for this edition, illustrating many of the stones and buildings with good-quality images, often showing features explained in the text. Spiral binding is proving a popular feature for 'field guides', and for this publication helps to make it easier to handle when walking in a busy city centre. The maps are on the inside covers in pull-out sections. This enables the map and the text to be read as a 'single page', another very helpful feature. The maps are clear and easy to use and not cluttered with superfluous information. Four walks are detailed in the text and each map covers an area of the city centre with between 15 and 23 locations to visit on each walk.

The attractive cover, front and back, highlights key buildings and a range of stones to be seen en route, and gives a strong visual appeal to the publication. Manchester clearly has a good range of building stones from the British Isles and from abroad, and this publication illustrates them very well. Often, both the trade name and the geological name are given for the modern cladding stones, together with a place of origin, where known.

The text is limited, but that is perhaps how it should be in such a publication. The balance of text and images is good and the font size readable. However, it is a strange editorial decision that a large section of text from an inscription, which can be read on the walk, should occupy over half a page — while of general interest, the words have no geological significance.

Personally, I would have liked the route directions between the stone descriptions to be more distinct from the narrative — while a slightly smaller font size has been used, a different colour or indent may have made navigation through the text more user-friendly, especially when looking at the pages 'in the field'.

The seven-page glossary explains the geological terms mentioned in the main text. A small criticism is that: having read that crystals of feldspar in larvikite change in colour and brightness when viewed from slightly different directions — a property known as the Schiller effect — I turned to the glossary to learn that the Schiller effect is a "…lustre changing with the angle of incident light. Best seen in plagioclase crystals found in larvikite". I left the glossary none the wiser.

There is also a link at the end of each walk to the Manchester Geological Association's website (including a QR code) for further information about the building stones of Manchester. This should prove an excellent way to keep the reader up to date with any changes to the itineraries. However, at the time of writing this review there was no reference on the website to the publication. Today, in any busy city centre, buildings come and go and their façades can be altered considerably on the whim of a new landlord, sometimes destroying the facing stone and leaving the guide holder scratching his or her head as to what they should be looking at. This can make a walking publication out of date very quickly, but hopefully the Manchester Geological Association has found a practical solution to this perennial problem.

There is no price on my review copy, but the internet informs me the purchase price is £9.95. For a few hours of gently-paced geology and a handy reference tool this booklet should make a useful addition to a geologist's bookshelf for when next visiting Manchester's city centre.

— Geoff Downer, BSc Hons (Open)

The end-Permian mass extinction event

Paul Goodrich

[Unfortunately, Paul Goodrich was unable to write up his lecture as an article for the OUGS Proceedings*. Although we provided a near verbatim transcription of his lecture recording to him there were many queries in the text and it was not possible to produce an acceptable article from the transcription text. Therefore we are able only to publish an abrstract from the Symposium brochure — Ed.]*

Abstract

As with all the 'Big Five' mass extinctions, no single factor or event can be held responsible for the most catastrophic and irreversible devastation of life on Earth that occurred *c.* 250mya. Nor is it likely that one single event can be described as the Permo-Triassic Mass Extinction — rather pulses or cumulative episodes with a final great spike in species mortality at the Permian–Triassic geological and temporal boundary. Each event compounded the effects of the others. Some possible contributing factors are controversial and remain contentious. In the light of Walter Alverez's work on the Cretaceous-Tertiary (K-T) Mass Extinction and the identity of the Chicxulb Crater as ground zero for the Extinction Level Event (ELE) that saw off the dinosaurs and much else, Dr Mike Rampino's suggestion of a similar bolide event at *c*. 252mya is a great deal more plausible than it might have been if theorised before 1980. The lack of a guilty crater remnant with a convenient iridium indicator in the rock record does not necessarily rule it out as a possible contributing event.

The vast Siberian Traps, the great terraces of basalts originally covering up to 7 million square kilometres, and 2–3km deep at the volcanic centres must certainly have accelerated the demise of genera during this time. The Large Igneous Province (LIP) event and its CO_2, SO_2 and fluorine output would have had worldwide implications. As an agent for disruption to methane and methane hydrate stores, and over so prolonged a period, this great extrusive episode in Earth history must also have led to loss of marine and terrestrial life, almost to the point of no return. What remained carried genetic material enough to ensure that basic body plans and [biological] Kingdoms survived, but only just. There were no fern spikes, no explosion of diversification, visible in the strata above the Permian-Trassic boundary, but succession after succession of barren rocks, lifeless braided river sediments, and great aeolian tracts with no inhabitants. Life took up to 10 million years to begin again in earnest. It took much longer before the Earth saw again the fecundity and diversity of the Carboniferous Period. Other factors have been suggested to account for the devastation: a gamma ray pulse from a proximal neutron star, a solar event, or, like the Lunar Mares, the Traps are possibly a result of a meteor strike — with any resultant crater overwhelmed by basalt floods triggered by the bolide.

There is much yet to discover and the definitive story of the 'Great Dying' has yet to be written. Discussion and research continue.

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Book review

Gill, Robin 2015 *Chemical Fundamentals of Geology and Environmental Geoscience* (3rd edn). Oxford: Wiley Blackwell (ISBN 978-0-47065-665-5, 267pp; paperback, £32.50)

Geology is primarily an observational science. Some observations may be explained by comparison with present day processes. Other observations, those where there are no comparable present-day processes, or where the process took place within the Earth, may be explained by assuming that the laws of physics and chemistry apply uniformly in space and time. For these reasons the geoscientist needs to study the principles of physics and chemistry.

This outstanding book provides an excellent introduction to the chemical principles relevant to the geosciences. Although written at a relatively elementary level, the explanations provided are non-trivial and complete, thus providing a secure foundation for more advanced studies.

The first four chapters concentrate on the 'bulk properties' of matter. Chapters 1 and 2 explain thermodynamic principles and apply these to discuss equilibrium in geological systems. Chapter 3 concentrates on kinetics: the rates at which processes proceed. Chapter 4, on aqueous solution chemistry, contains an excellent explanation of non-ideality and applies this to natural waters of increasing ionic strength.

In contrast, the following four chapters concentrate on matter at the atomic and molecular scale. Chapter 5 introduces atomic structure using modern wave-mechanics concepts at an elementary, but non-trivial, level — I wish that I had had access to this material as a first year undergraduate! The link between the shape of electronic orbitals, the shape of molecules and molecular properties is clearly explained. Chapter 6 concentrates on the Periodic Table by linking chemical properties to electronic structure, while Chapter 7 introduces bonding. Chapter 8 discusses the structure and properties of silicate crystals and melts, including an explanation of how the optical properties of minerals relate to structure and bonding.

The final three chapters build on the previous chapters. Chapter 9 reviews some geologically important elements. This chapter is not a mere catalogue, but contains much useful material (in separate boxes) that explains general concepts such as element incompatibility, the behaviour of metals in aqueous solutions and the link between transition metal chemistry and the colour of minerals. Chapter 10 is devoted to radiogenic and stable isotope geochemistry, while Chapter 11 considers the formation and relative abundance of the elements in the universe.

The book is beautifully produced with clear text, together with well-drawn and informative diagrams. It has been well proofread — I encountered very few errors, most of which are minor, easily spotted and quickly corrected. All chapters have a set of exercises with full answers provided in an appendix. All in all, this book is excellent and highly recommended.

— Duncan Woodcock, BSc Hons (Open), part-time PhD student

Reservoir quality within the Rotliegend sandstones of the southern North Sea

Jon Gluyas

Abstract

The Lower Permian Rotliegend sandstones form the most important gas reservoirs in Europe as well as being minor oil reservoirs. Gas was sourced from the underlying carboniferous coals. Sandstones with a range in reservoir quality from multi-Darcie to micro-Darcie, that is so-called 'tight', occur around the edges of what we call the Southern Permian and Northern Permian basins. The sandstone depositional systems were considerably larger than individual gas fields and yet many fields show evidence of compartmentalisation and poor interconnected permeability. Segmentation and reduction of reservoir quality were caused by a combination of structural and diagenetic effects. The diagenetic events have been characterised and been dated and their occurrence can be correlated with major events in the geological history of the sandstones. However, the source and distribution of the main diagenetic minerals remains enigmatic and as such forecasting the distribution of poor and good reservoir quality difficult. Understanding how and where mineralogical cements precipitated with help targeting and improved recovery of gas from 'tight' sands as well as help us understand which reservoir intervals will make robust carbon storage sites.

Introduction

The giant Gronnigen gas field was discovered in 1959 (Whaley 2009). It is the largest field in Europe and tenth largest in the world. At discovery it contained about 100 trillion cubic feet of gas contained within Lower Permain Rotliegend sandstones. The discovery of Gronnigen led directly to exploration for similar gas reservoirs in the Southern Permain Basin (Fig. 1), the first of which, West Sole, was found in 1965 (Winter and King 1991). In the 50 years that followed discovery of West Sole, 100 Rotliegend reservoired gas fields have been found and developed in the UK sector alone, with comparable numbers of fields in the Dutch sector, as well as more in Germany and through to Poland (Doornenbal 2010). More discoveries and some field segments lie undeveloped. Currently non-economic or sub-economic such discoveries are typically small, or contain gas in tight, low-permeability reservoirs. In addition many of the developed fields have only modest projected ultimate recovery factors (Table 1). Thus despite the near pervasive occurrence of gas within the Rotliegend sandstones of the Southern North Sea, development has not been optimal and much gas remains to be won. The aim of this paper is to examine the controls on reservoir segmentation and quality within the Rotliegend sandstones.

Table 1 Gas in place, gas reserves and recovery factors for UK Rotliegend reservoir gas fields (data from Gluyas and Hichens 2003)

field	*gas in place (bcf)*	*reserves (bcf)*	*expected ultimate recovery (%)*
Barque	3020	1366	45
Camelot	279	251	90
Clipper	1171	753	64
Corvette	236	211	89
Davy	200	175	87
Bessemer	130	100	80
Beaufort	40	32	80
Brown	35	25	70
Gawain	288	196	68
Guinevere	100	90	90
Indefatigable	5600	4700	84
Johnston	567	380	67
Leman	14689	13320	91
Malory	99	75	76
Mercury	124	82	66
Neptune	341	286	84
Pickerill	900	500	56
Sean North	260	234	90
Sean South	610	488	80
Sean East	143	127	89
V-Fields	2593	1841	71
Viking	2990	2895	97
Phoenix	845	507	60
Windermere	104	86	82

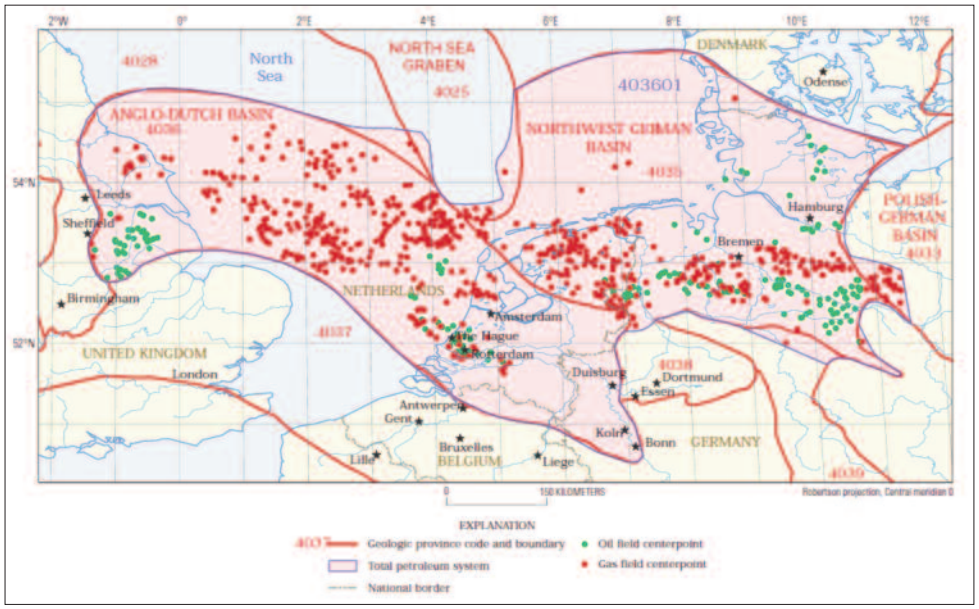

Figure 1 The Southern Permian Basin (comprising Anglo-Dutch, Northwest German and Polish German basins) (from Gautier 2003).

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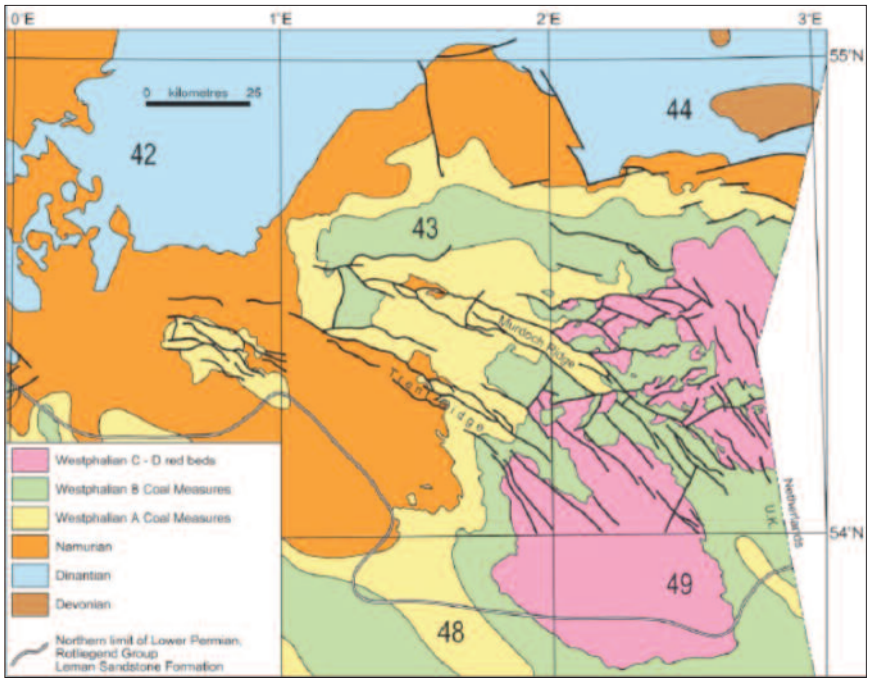
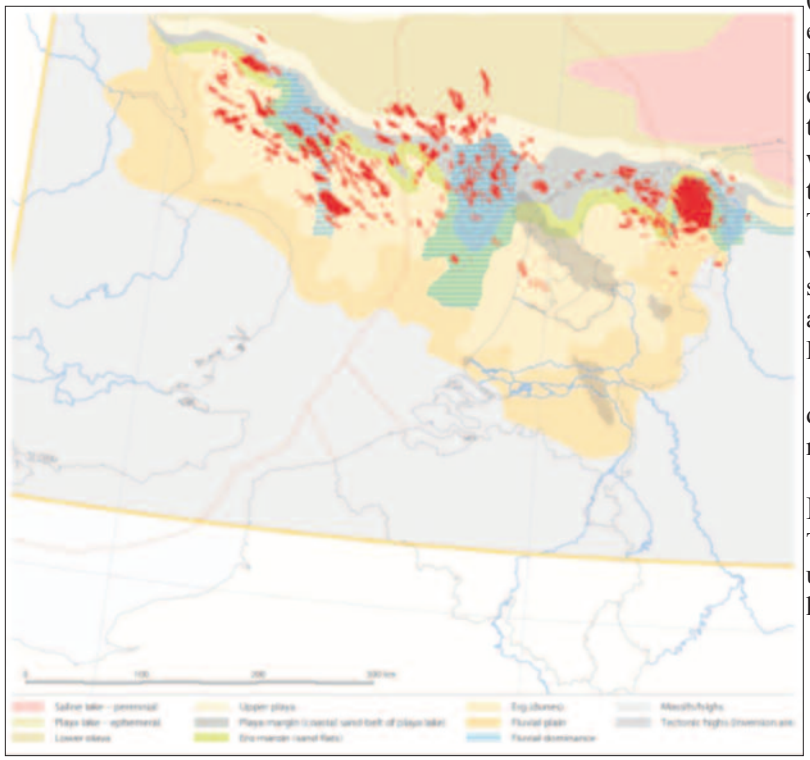
Depositional system

In broad terms the Southern Permian Basin of Europe comprised a large non-marine basin (1,500km E–W × 500km N–S) the centre of which was occupied by an ephemeral lake called the Silver Pit Lake. Fringing the lake and to the edge of the basin were sands with subordinate muds deposited as aeolian dunes, fluvial sandbodies and sabkha mixed sandstones and mudstones. The substrate to the basin was an eroded but not peneplaned terrain of Carboniferous and Devonian strata (Fig. 2). Local topography in the basin gave rise to the presence of isolated patches of basal Rotliegend sandstone in the basin centre in what otherwise was the mud dominated Silver Pit lake.

Figure 2 Subcrop to the Base Permian Unconformity in the Southern North Sea (from Underhill 2003; reproduced with permission from the Geological Society).





The sandstone-dominated facies belts are enormous and cover many thousands of square kilometres. These facies belts are substantially larger than the footprints of even the biggest fields (Fig. 3), although some fields cross-cut the facies belt boundaries (Fig. 4, *opposite*).

Reservoir segmentation

Many of the Rotliegend reservoired fields are segmented. This was often noticed in the early developed fields as a mismatch between the volume of gas as calculated form geological and from geophysical analysis of the mapped field volume, which most often was larger than that derived by reservoir engineers from decline analysis of the production wells. Moreover, wells drilled only short distances apart commonly displayed different pressures. The assumption was that many fields were faulted, with the faults acting as barriers to fluid flow. Other than a few small clues seen in cores and granulation seams we had little evidence as to what was causing the compartmentalisation. Only when 3D seismic surveys became common were the faults revealed (Fig. 5, *opposite*).

Fault lineaments trending SW–NE can be mapped from the 3D seismic data. The trend of these strike slip features is co-incident with structures in the underlying Caledonian basement. Within the Rotliegend the zones are characterised by quartz cemented granulation seams with negligible cross-seam permeability (Barr 2007). Barr dates the sealing fractures to the end Jurassic, when faulting at high temperature and pressure gave rise to the cataclasite rocks.

Barr (2007) also points to uplift in the Tertiary as causing the then brittle rocks to fracture, leaving open transmissive faults. These processes, however, might not always have been the case. Gluyas *et al.* (1997a) report on findings from an investigation of diagenesis within the Rotliegend reservoir of the Amethyst Field. Many of the Tertiary inversion faults in Amethyst are cemented by barite. Isotope evidence was used to show that the source of the sulphate was the overlying Zechstein, while the barium was inferred to have been derived form the formation waters within the underlying Coal Measures. The barite precipitated when the two sets of formation waters mixed during uplift. This same barite cement can be seen at Cullercoats on the north-east coast of the UK, where a heavily fractured zone adjacent to the Ninety Fathom Faults is pervasively barite cemented (Fig. 6, *opposite*).

The presence of cemented fractures means that the drainage volumes per wells in Rotliegend fields are commonly modest (Fig. 7, *page 52*).

Reservoir diagenesis

The diagenetic mineralogy of the Rotliegend sandstones is unusual in that it is dominated by illite. The illite occurs as hairy projections from the quartz grains and may form in

Figure 3 Major facies belts within the Southern North Sea with superimposed field outlines — upper part of the Slochteren Formation and its equivalents (Rotliegend, Late Permian) (from Doornenbal and Stevenson 2010).

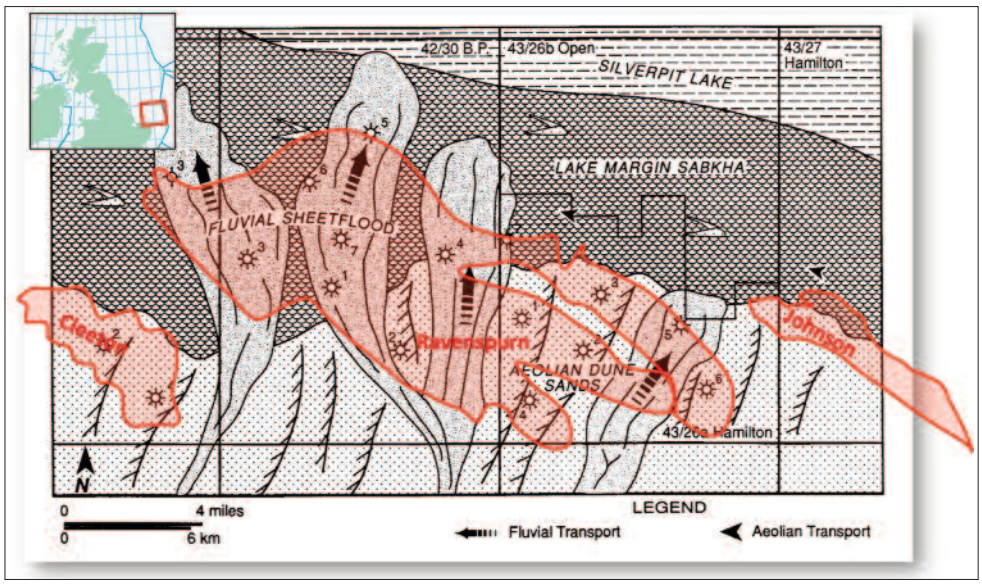
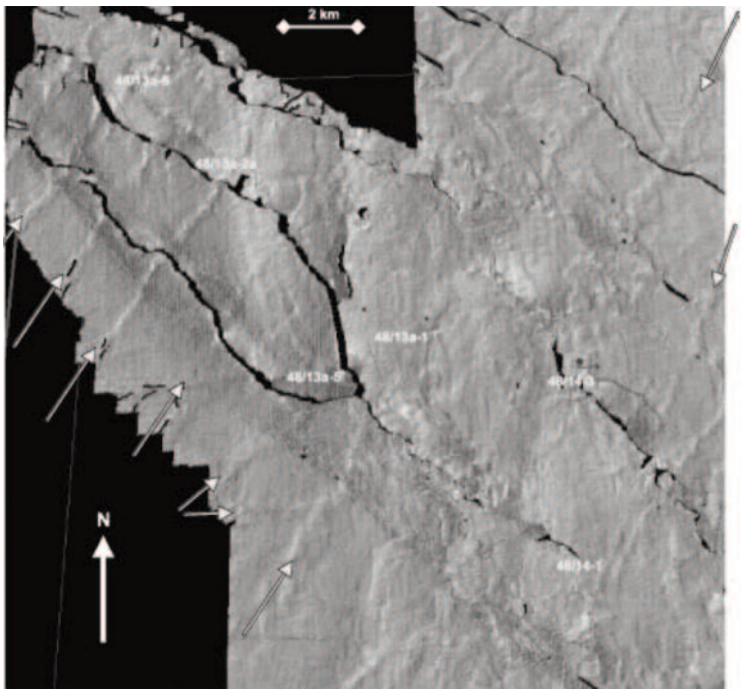


Figure 4 Dune/lake margin and the outline of the Ravenspurn and adjacent fields (redrawn and modified from Ketter 1991; reproduced with permission from the Geological Society).

Figure 5 Illuminated top Rotliegend Barque Field. The arrows mark strong SW–NE lineaments (from Sarginson 2003; reproduced with permission from the Geological Society).



excess of 15% of the rock (Fig. 8, *overleaf*). When present in quantities in excess of about 10% the presence of illite is seriously detrimental to permeability, although the porosity may not be significantly affected. Illite-cemented sandstones typically have a permeability of *c.* 1mD, *c.* 1000 times less than an uncemented sandstone.

Illite is not the only diagenetic cement in the Rotliegend. A schematic of the mineral paragenesis is shown in Figure 8. In addition to illite, the sandstones also contain other clay minerals (kaolinite and chlorite), quartz, carbonates, sulphates and sulphides. However, all of the other minerals tend to be present in lesser quantities than illite.

It is possible to date the time of precipitation of the illite using the K–Ar method because it contains *c.* 5% potassium. Many researchers have dated the illite and all yield ages of *c.* 150–160Ma — that is, end Jurassic times (Robinson *et al.* 1993). With a known date, and therefore temperature from the area's burial and thermal history, it is then possible to calculate the isotopic composition of the water from which the illite and other contemporaneous digenetic minerals crystalised using 18/16 oxygen isotope ratios. From such an analysis it is clear that the early diagenetic chlorite along with the later diagenetic dolomite, kaolinite and illite precipitated from water that was likely to have originated as Zechstein (Upper Permian) sea water modified by water–rock interaction. The temperature of precipitation was *c.* 50°C for the chlorite, *c.* 100°C for dolomite, and between *c.* 120°C and 200°C for the kaolinite, then illite (Gluyas *et al.* 1997b). Ferroan dolomite and quartz precipitated at similarly high temperatures, but not from the same water. Ferroan dolomite and quartz precipitated from meteoric water of the same composition as can be found in the North Sea Rotliegend reservoirs today. From the oxygen isotope data in the formation water it is inferred to be Jurassic rainwater.

Given these data it seems likely that most of the mineral cements precipitated at the end of the Jurassic, initially from evolved Zechstein water and latterly from what is believed to be Jurassic rainwater. These diagenetic events are coincident with the deep, high-pressure, high-temperature faulting dated by Barr (2007) and the known date for the rifting of the basin. It thus seems likely that rifting led to uplift of the rift shoulders and in so doing allowed penetration of meteoric water deep into the basin.

Distribution of high and low quality reservoirs

While the sequence of diagenetic events can be correlated with major basin-forming processes, including end-Jurassic rifting and Tertiary inversion, we still do not understand what caused the dramatic variation in diagenetic cement content of these sandstones and how so much illite can precipitate in some sandstones (Fig. 9, *overleaf*). The Rotliegend sandstones of the

Figure 6 Barite fracture cements, Rotliegend sandstone, Cullercoats north-east England (coin is 25mm diameter; photo by J. Gluyas 2010).

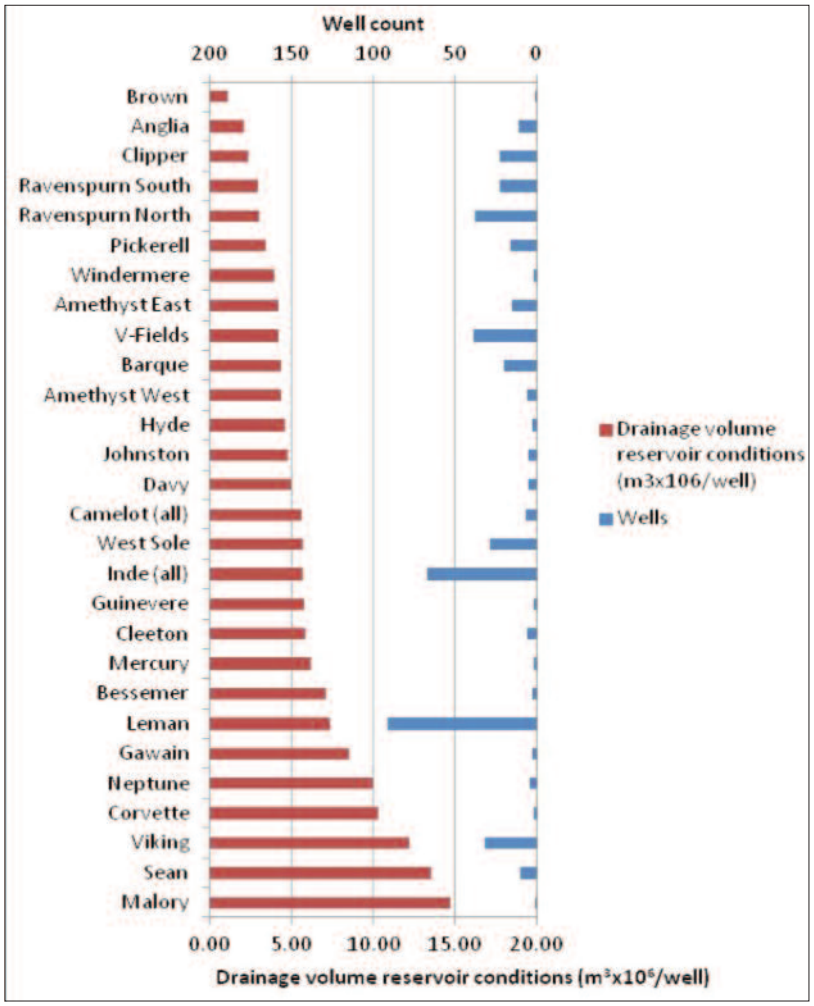
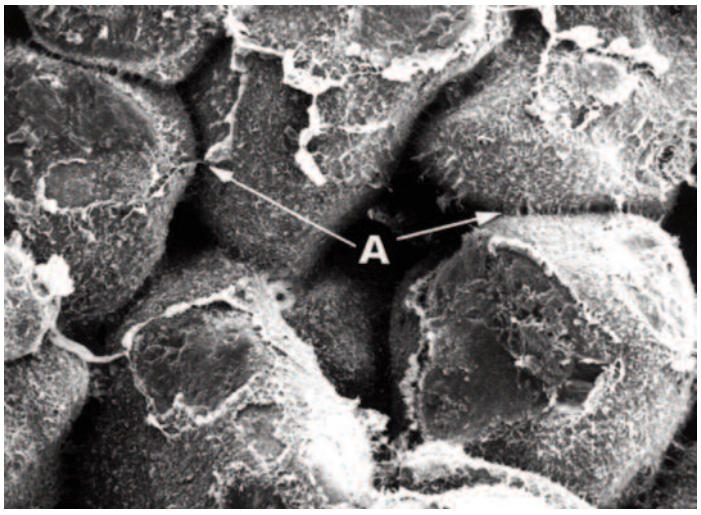


Figure 7 Drainage volume per well calculated for Southern North Sea gas fields. The data were calculated by dividing the total field production to end 2012 by the number of wells in each field (units = million cubic meters reservoir volume).

Figure 8 Pore bridging (A) hairy illite (grain diameters c. *150 micrometers), scanning electron microscope photomicrograph, Ravenspurn Field (photo by J. Gluyas 1983).*



Ravenspurn fields have abundant illite, while those from the adjacent Cleeton Field are almost wholly uncemented (Fig. 10, *opposite*). Moreover, those sandstones with abundant illite appear to have imported silica, potash and alumina. Silica can be derived locally from stylolites and potash is a component of the formation water, but movement of large quantities of alumina is not feasible and geochemical analysis indicates that dissolution of feldspars in the sandstones could not have supplied sufficient alumina (Gluyas and Leonard 1995). Research is currently underway to determine why some fields carry almost no diagentetic cement while other fields have substantial quantities, as well as ongoing work to determine the origin of the illite cement.

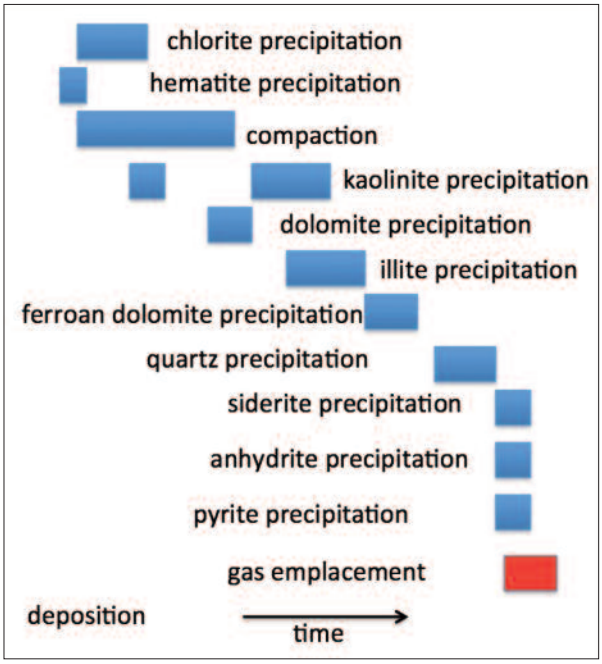
Conclusions

The Lower Permian Rotliegend sandstones form the most important gas reservoirs in Europe and they have been exploited for almost 60 years. Despite their importance they are of variable quality. Some fields are heavily compartmentalized, while in others the reservoir, though porous, is often of low permeability; and because of these limitations on quality, recovery factors can in some instances be as low as 50%.

These same Rotliegend reservoirs, and in particular the depleted gas fields, are likely to be important for storage of CO_2.

In order to continue to exploit the remaining gas resource as well as to develop some fields for CO_2 injection it is important to better understand the diagenetic history of the sandstones. Work continues.

Figure 9 Diagenetic history of the Rotliegend sandstones within the Ravenspurn Field (from Gluyas et al. *1997b).*



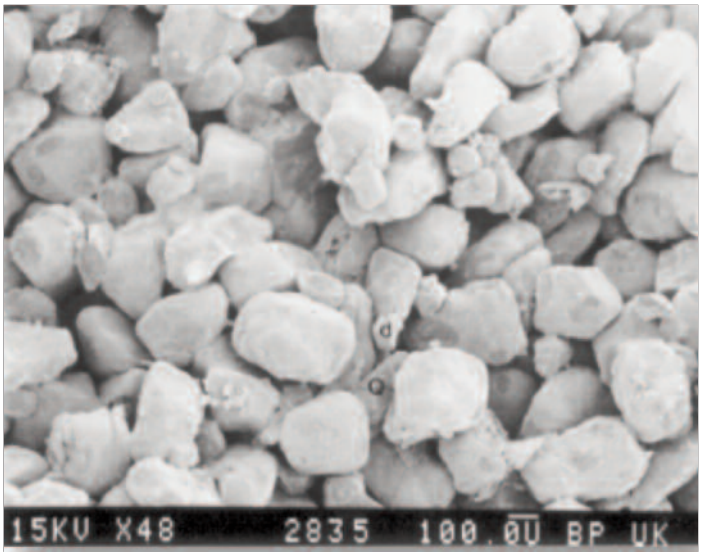


Figure 10 the Rotliegend reservoir within the Cleeton Filed is largely uncemented and has permeabilities in excess of 1D (photo by A. Leonard 1994).

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Book review

Harvey, Adrian M., and Mather, Anne E. 2015 *Classic Geology in Europe 12: Almeria*. Edinburgh: Dunedin Academic Press Ltd (ISBN paperback 978-1-78046-037-6; e-pub 978-1-78046-527-2; Kindle 978-1-78046-528-9; paperback and e-book £24.99, Kindle £21.25)

I was excited when I saw this was available, as it is the third iteration of Anne Mather's guides to this area, succeeding the BSRG Field Meeting Guide Book she wrote with Martin Stokes (1999) and the Blackwell's Field Guide to the Neogene Sedimentary Basins (with Martin, Harvey and Braga), which was an expanded version of the 1999 publication, in 2001. I have used these two former two guides, plus experience from other visits to the area to run field trips there over the last 15 years.

The Dunedin book is an improvement on previous versions in terms of colour plates and figures: these are a great help, particularly for a newcomer to the area. A gripe I have is that some figures have been scaled down to the extent that the labels and legends on them are hardly legible, even for my myopic vision. This new guide has also been reduced in length to about two-thirds of the previous version, so something has had to go and, in terms of material covered, where the Blackwell's book stretched its wings and flew out into the heady realms of the older Nevado-Filabride, Maláguide and Alpujárride basement complexes, the Dunedin version returns to its Neogene Basin roots.

Don't get me wrong: the Neogene Basins of Almeria are world-class examples of these marginal features and, because of the semi-desert climate and lack of vegetation, have wonderful exposure, making them a real luxury in terms of field work localities. However, I was disappointed to find that the basement rocks, and even the wonderful Neogene volcanics, only have cursory cover. Perhaps these aspects should have a guide in their own right, but they are so much a part of the overall geology of the area that I feel they warrant more coverage here, especially since the title of the book has misleadingly been changed from 'Neogene Basins' to the all-encompassing 'Almeria'.

The book is divided into two main sections: Part I covers 'The main themes in the geology and geomorphology of Almeria' and Part II includes details of keynote sites and seven itineraries. There are also useful appendices, including a Geological, Neogene and Quaternary timescales, a glossary and a short section on logistics, which would be useful for someone new to the area. And indeed, for anyone who is new to the area, there is plenty to go and look at — it is aimed at the undergraduate or the enthusiastic amateur, so if you are planning to go there, don't reject it out of hand because of its lack of hard-rock interest! I won't be throwing out my previous guides though.

— Linda Fowler, BSc (Open)

Book review

Upton, Brian 2015 *Volcanoes and the Making of Scotland* (2nd edn). Edinburgh: Dunedin Academic Press Ltd (ISBN 978-1-78046-056-7; hardback, 248pp; £24.99)

This is a well-produced book, 240mm × 160m and 20mm thick, but quite heavy so you probably wouldn't carry it in your rucksack! Printed on shiny paper, reading some of the diagrams can be a bit tricky in certain light.

The book comprises 12 chapters, a bibliography and an index. I thought that having no glossary would be a problem, but technical terms are explained at least once within the text. They can be found in the index, though you then have to turn to the particular page for definitions — just a niggle really. The first four chapters give an introduction as to what to expect from the book: information on how volcanoes form, plate tectonics, geologic time, mantle plumes, magmas, pyroclastics, lava and igneous rocks. I found these chapters a really good revision of basics, with some new information too. Upton uses modern analogies too. There are lots of diagrams, although references to them are sometimes not as clear as they might be. The photos are generally of good quality.

The next seven chapters go into detail about the various volcanoes that have formed in 'Scotland'. And this is where the book becomes somewhat unusual (which Brian Upton admits!). He takes the formation of the various igneous centres chronologically, but from the most recent backwards. This is not something I am used to — I tend to think in terms of old-to-young, in geological chronology, not vice versa. Also, when making something, you usually start at the beginning not the end. However, his point is that there is more evidence available from the most recent volcanoes about their formation and history. He then applies this to the more limited evidence of the older areas, 'imagining' what might have happened, say, in the Devonian, while pointing out that it is 'informed guesswork' and that we will probably never know: so much time, so much erosion, so little left! There is a comprehensive section on the Edinburgh volcanics, with very specific examples. Chapter 11 concerning the Pre-Cambrian is particularly fascinating, and shows the information available through geochemical analysis. Chapter 12 contains a summary. In a nutshell, Scotland is a graveyard of volcanoes.

The book took very careful reading. Rereading of some sections was needed, as the story is very complicated — I think I knew it was, but not quite *that* complicated. While this is a serious book, Brian Upton's style includes the colloquial and he does add humour on occasions (but I'll leave the reader to find these!).

Overall, I thoroughly enjoyed the book and I think it would be a valuable addition to your bookshelf, especially if you are interested in Scottish geology. I will take it with me every time I am in Scotland, albeit not in my rucksack.

— Jane Michael, BSc Hons (Open) Nat Sci (Earth Sciences)

Mining in the Zechstein evaporites at Boulby Mine

Neil Rowley MSc C Eng FIMMM

Thalia © 2015

Introduction and history

Boulby mine is situated on the North Yorkshire coast between Teeside and Whitby, near the village of Staithes. The Permian and Zechstein are overlain by some 1,000m of younger rocks at this point (Fig. 1).

The deposits of potash were found during exploration for oil and gas in the 1930s. Previous speakers have described why petroleum engineers are very interested in our halite rocks, as they form a really good cap rock for migrating oil and gas. Most of you have had chance to examine the samples of these halite rocks *[on display at the Symposium — Ed.]*. Initial impressions are that these rocks are very friable — they will shatter easily when struck with a hammer; however, if halite rocks are compressed by burial deep within the strata, they show very plastic properties and form a really good seal. We see this plastic flow readily in our mine workings. When we make a tunnel in these rocks, the floor rises up within weeks of exposure. It actually moves in a fluid-like way — a very interesting rock.

The potash produced at the mine almost all goes to make fertilizer. In the 1960s ICI was a big producer of fertilizer and made the brave decision to invest in this large new mine to exploit these reserves. Such projects are not cheap, and their initial investment would have been in the region of £800,000,000, in modern-day equivalent. The shafts were reported as being the deepest in Europe at the time. The railway line needed to be reinstated, and a large processing plant built— all high cost items.

Things didn't go well in the early years; production didn't pick up as well as had been hoped, conditions in the mine were difficult and accidents were common.

ICI made the decision to let the mine go in the late 1970s, and despite their large investment they sold it for a nominal sum to Anglo American, who had been one of their partners during the mine construction.

The mine continued in Anglo American ownership right up to 2002. During this period the mine was finding it difficult to make a profit owing to the low world price of potash and the ever-increasing distance of the mine workings from the shafts.

In 2002 Anglo put the mine up for sale and it was bought by ICL who have invested heavily in the mine and who have benefitted from a steep rise in the world price for potash products. Current indications are that the mine should have several good

Figure 1 ICL Fertilizers Boulby Mine.

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years of life remaining, but it will need to be flexible to cope with the ever-changing world in which we exist.

You will probably be aware that there is currently an application for permission to build a new mine to the south of Whitby. This is not from ICL, but rather from Sirius Minerals, a competitor company. Both Boulby and the proposed new mine are located within the North York Moors National Park.

Any such developments are understandably subject to very tight planning restrictions. The landscaping and architectural standards that were applied to Boulby will not be sufficient in this modern age to gain permission. The new mine will need to be pretty much invisible.

However, the economics show a good case for allowing a tightly controlled development. Boulby employs more than 1,000 people and makes a contribution of well over £100 million per year into the local economy. A similar new mine would be of great economic benefit to the local area.

Minerals mined at Boulby

The main potash ore that we mine is called sylvinite. Sylvinite is a mixture of potassium chloride (KCl), sodium chloride (NaCl) and clay. The ratio of the minerals does vary greatly. We aim to mine ore with a KCL grade of higher than 30%, but the deposit can vary from 0 to 60% KCL, so much exploration drilling is required to identify the best areas to mine (Fig. 2).

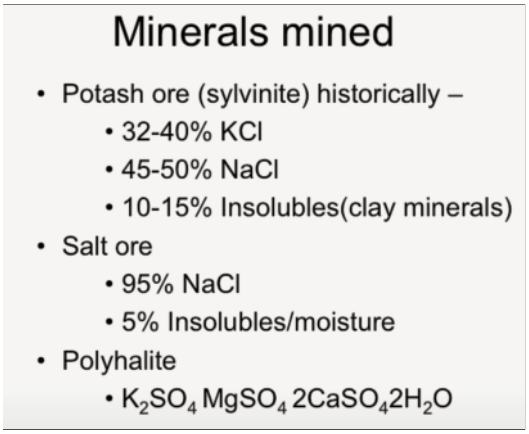

Figure 2 Minerals mined at Boulby.

We also mine substantial quantities of de-icing salt. This is a relatively low-value product in relation to potash, but it is essential to mine the salt in order to make the long-term tunnels in the mine. Halite and sylvinite have similar compressive strengths, but it was found early in the life of the mine that a tunnel made in sylvinite will start to fail very quickly. It may last for four or five years in the shallower parts of the mine, but the tunnels in the deeper parts of the mine can only remain of use for one or two years. A tunnel in the halite will, however, remain open for 30 or 40 years if properly engineered. So wherever we go to mine the sylvinite we will follow the development with two tunnels in the halite to provide long-term access. This produces the salt that can be sized and graded to sell for de-icing roads during the winter months.

More recently we have been developing some 150m below the sylvinite to access polyhalite ($K_2SO_4.MgSO_4.2CaSO_4.2H_2O$). It is quite a new product for us. Geologically it is perhaps best described as a naturally modified anhydtite. This can be used as fertilizer directly, without the need for extensive processing. There is currently a lot of interest in sulphate fertilizers, one of the factors being that in the past coal-fired power stations have been putting sulpher dioxide into the atmosphere, which then adds sulphates to the soil during rainfall. Now the farmer needs to buy sulphate fertilizers to maintain the level of essential sulphate in soil.

The world market for polyhalite is currently only 130,000 tonnes per year. We are at the moment the only producer and that is what we mined last year. We expect that the market will develop steadily over the coming years. The new mine proposed to the south of Whitby is being primarily designed to produce polyhalite, due to the difficulties of mining sylvinite at depth, and will be aiming to produce several million tonnes per year very quickly. It will be interesting to see if the world market will develop at a pace sufficient to accommodate this supply level.

Some statistics

Typically Boulby produces *c.* 2.5 million tonnes a year of sylvinite. This is refined down to yield *c.* 750,000 tonnes of finished potash products.

Rock salt: I think that the most salt that the mine has sold in a year was one million tonnes. In recent years the winters have been quite mild and we have been able to get by on lower salt driveage. Last year production was < 0.5 million tones.

Polyhalite: Production was 130,000 tonnes last year and will be 250,000 tonnes this year [2015]. It is expected to rise to 500,000 tonnes next year. Future tonnages depend very much on the development of the world market for the product.

The mine generally can produce 10,000 to 12,000 tonnes a day. The limit on the mine is what can be raised up the shafts. I believe that the record for tonnage up the shaft in one day is more than 14,000 tonnes, but the need for time to be spent on shaft maintenance means that this amount cannot be achieved on a regular basis.

People: There are 1,100 direct employees, and another 100–200 contractors. There are also many more people in the community who have their livelihoods connected to the mine. It is a very big employer in the Northeast of England.

ICL doesn't just own the mine, it also owns part of the railway. Being in the National Park we are limited regarding how many road wagons can get out, and hence the great majority of product goes by train. Our responsibility for the track extends as far as Skinningrove Steelworks.

The company also operates a dock on the River Tees. This dock is crucial to the business, facilitating distribution of bulk cargoes worldwide. Half of the product sold goes within the UK, the other half can go almost anywhere in the world. A lot of it is going into northern Europe at the moment.

Potash is applied to the land in the spring. There are two springs in the year. The Southern Hemisphere has its spring at a time when the market is quiet in the Northern Hemisphere. Ships to Brazil in the summer certainly help to even out supply through the year (Fig. 3, *opposite*).

The dock is also used for the distribution of the de-icing salt that we mine. Most of the salt is for use within the UK, but coastal sea transport provides an environmentally sustainable means of moving large tonnages. Many cargoes go to the east coast of Scotland, but also much of south-east England is also supplied by sea via the Thames or Shoreham. The occasional cargo will go to the east coast of the USA.

Figure 3 Ship loading de-icing salt at Tees Dock.

Economics

Potash is essential to maintain world food supplies. Some of the greatest users are Brazil, China and India. They have big populations and big agriculture, but little indigenous potash. If the potash in the ground is not replaced after crops have been harvested then yields will decrease. There should be a good long-term market for potash products for many years to come.

We are a fairly small player. We don't have much say about what happens to the world price. As you know, commodity prices can vary greatly. All we can do is mine as efficiently as we can at Boulby.

If world price is low, then we can defer capital expenditure and concentrate on the products that offer the best value return. However, as the distance from the shafts to the working area increases over time, then the fixed costs rise. The limit of economic working is a difficult thing to predict. Hopefully, with our range of products we may be able to continue mining for many years yet.

Capital does need to be spent, however, to maintain the integrity of the mine and to produce a good quality product.

Possibly the most noticeable capital project in recent years has been the replacement of one of the head towers at the shaft top. This was a major civil engineering exercise. The old tower was starting to show signs of structural deterioration and replacement was essential to maintain the production capacity of the mine. The mine had to remain operational throughout as much of the construction phase a possible, so it was planned to build the new tower alongside the old one and then remove the old tower and slide the new one into position during a three-week summer shutdown period. This was a noteworthy feat of engineering (Fig. 4).

The operation was very successful, and the new tower was up and running within the allotted time. As you will see from the photographs the appearance of the new headframe was initially very much more like the traditional coal mining structures that we have been used to in Britain. However, in order to comply with the requirements of the National Park planning authorities and to make the shaft top area more weather resistant, the steel frame has now been enclosed in a concrete shell, which maintains the visual appearance of the original design.

Other major capital projects have involved making the refinery process more efficient and in developing the facilities to deal with the production of polyhalite.

Operation of the mine

Boulby has two principal shafts, each 1,100m deep and 5.5m in diameter. To ventilate the mine the air is forced into the 'downcast' shaft by the surface fans. The air travels all around the underground workings and emerges at the other shaft, which unsurprisingly is referred to as the 'upcast' shaft.

The downcast shaft is used to transport men and materials. It is fitted out with a large three-deck cage and a small counterweight cage. The main cage can accommodate 65 men. This enables pretty much a full shift of men to enter and leave the mine together. Materials are also transported on this cage, principally on pallets handled on and off by fork lift truck. Larger items can be suspended inside the cage if the decks are removed. A Ford Transit van can just fit inside the cage, suspended by its back end.

The upcast shaft is used to hoist the rock to the surface, but it also carries the hot, damp, salty air out of the mine. There is quite a significant corrosion threat in this area, which needs to be carefully controlled. The shaft is shut down at seven o'clock every morning for inspection and maintenance, and this work usually continues to around mid-day.

The mine works 24 hours a day, seven days a week, and production doesn't stop during shaft maintenance periods. There are several large bunkers underground that can store up to 30,000 tonnes of rock. Production continues into these bunkers during shaft maintenance periods. Once the shaft does resume its normal work then it operates with two 23-tonne skips at a rate of 32 skips per hour. This gives a winding rate of more than 700 tonnes per hour, which can generally cope with normal production and clear the bunkers before maintenance needs to start again the next day.

Figure 4 The new headframe alongside the old ready for the changeover.

Figure 5 Froth flotation.

Mineral processing

As the sylvinite rock is hoisted to the surface conveyors transport it into the processing plant. The primary aim of the plant is to separate the KCl from the associated NaCl and clay (Fig. 5).

The material is initially crushed to physically separate the mineral particles. It then passes to the froth flotation cells. Here an agent is added to produce bubbles. The choice of frothing agent is critical because the process depends on the surface tension of the bubbles attracting potash to stick to them, but not attract the salt or the clay particles. At Boulby, guar gum is used in combination with an amine. You will see from the photograph that this works well and the potash coated bubbles rise to the top of the cells while the salt and the clay sink to the bottom. The potash flows over from the cells into centrifuges, which reduce the moisture and then on into gas-fired drying kilns to produce a completely dry KCl product, which can be pressed into cakes and then broken-up to form a granular product. The moisture from the dryers forms the plume that you see emerging from the chimney.

Some of the KCl goes into solution and this is recovered by crystallisation. The resultant white crystals are 99% pure KCl and are sold into the industrial market.

But remember, only one-third of the rock is potash; two-thirds are rock salt and clay. Because the material has been pulverised down, it is too fine for use as de-icing salt and too dirty to be refined economically into the food market. As with all the other potash mines in the world it becomes a waste product. Our location by the sea is ideal for disposal. The brine and clay minerals can be pumped under permit into the sea about one mile offshore with very little environmental impact. Some sedimentation of the clay particles does occur on the seabed in the outfall area, but salinity levels recover to normal marine levels within meters of the discharge. The Environment Agency monitors the whole process closely, as do other external bodies.

Some of the sylvinite ore bypasses the separation process to be sold directly as fertilizer. Certain crops, such as sugar beet, have a marine ancestry and can tolerate some salt. The lack of processing makes it possible to designate this product as suitable for organic farming.

De-icing salt is relatively simple to process. As the salt from the development roads arrives at the surface it is crushed and screened to a size to suit the individual customer. A chemical anti-caking agent is added and the product is sent off to the dock by rail for onward distribution.

Polyhalite is also simple to process. The whole of the rock is saleable, so it just needs to be crushed to a size to suit the customer. Currently this is done using the same crushers and screens that process the salt, but a new, dedicated plant is under construction and will come into operation in 2016, enabling a much greater throughput of the product.

Geology

The shaft section gives an excellent introduction to the geology of the mine. The illustration is the original section drawn in the 1970s, so some of the terminology is now out of date, but I'm sure that you will have little trouble understanding it (Fig. 6, *opposite*).

The mine is built on the site of earlier ironstone mines. The Cleveland Ironstone main seam is not present in the Boulby shafts, but was extensively worked in the late 19th and early 20th centuries in the area immediately to the north of the current shafts.

To the mining engineer the main area of difficulty in shaft sinking was the Bunter (now Sherwood) Sandstone. This water-filled, loosely bonded sandstone forms one of Britain's main aquifers and presents obvious problems to anyone trying to sink a shaft through it. At Boulby two different techniques were used, one in each shaft.

The down-cast shaft was sunk using a cement injection technique. As the aquifer is approached, rings of holes are drilled and fine liquid cement is pumped into the strata, effectively blocking up the pore spaces and bonding the particles together. As sinking proceeds, further rings of holes need to be drilled to maintain the grout curtain ahead of the sinking. A water-tight lining is installed throughout the area. This can be something of a stop-start process and engineers often favour the freezing technique, which was used on the up-cast shaft.

In the freeze technique, holes are drilled from surface and refrigerated brine is circulated, turning the strata water into ice. Explosives are then used to blast through this mixture of rock and ice forming the shaft, and again a water-tight lining is installed. Once the lower limit of the aquifer is reached the freeze plant can be switched off, and the water will be held back by the newly installed lining. This technique can generally lead to quicker progress in the sinking of a shaft; however, in the case of Boulby the freeze plant was found to be underpowered and needed to be upgraded, causing the up-cast shaft to be completed almost a year later than the down-cast shaft.

Permian geology

I'm sure that you will all be familiar with the flooding and evaporation cycles of the Zechstein Sea during this period. The area that Boulby mines is part of the Z3 cycle. As the sea evaporated the various minerals crystallised out in order of solubility. First to crystallise was the calcium sulphate, forming gypsum/anhydrite, then the sodium chloride, creating a bed of salt some 60m thick beneath our normal potash horizon; and finally the potassium chloride, forming a layer of varying thickness — usually between 4m and 10m.

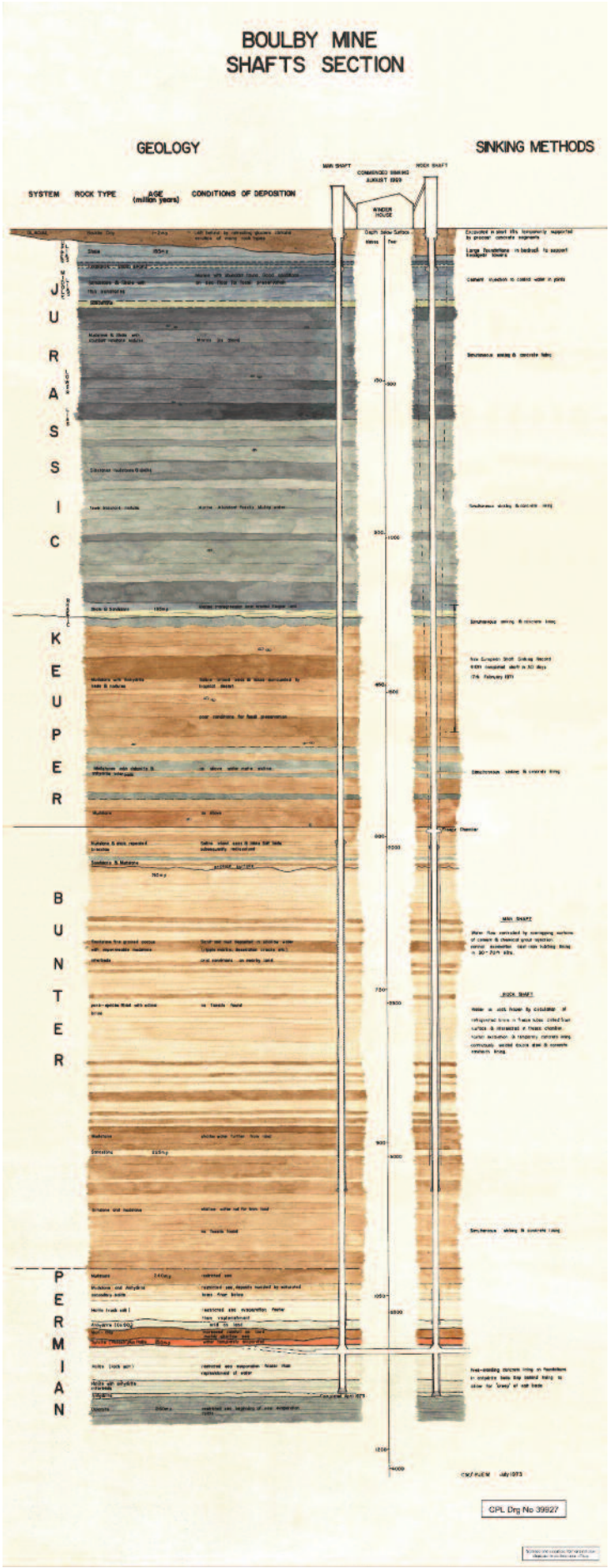

Figure 6 Shaft section.

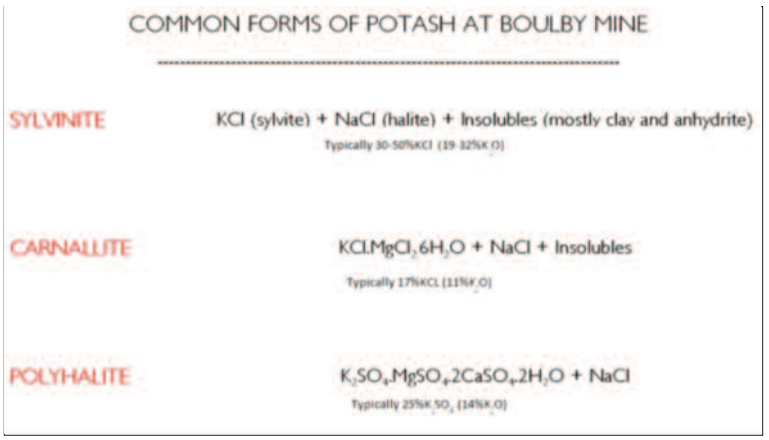

Figure 7 Common forms of potash at Boulby Mine.

The potassium chloride was probably initially in the form of carnallite ($KClMgCL_26H_2O$ +NaCl), but subsequent recrytallisation converted large areas to sylvinite (KCl +NaCl) (Fig. 7).

We see both forms of the ore in different areas of the mine, but sylvinite is the form of greatest economic significance. The carnallite has lower KCl content and has poor rock mechanics properties, making it unsuitable to work with our existing equipment. Sylvite is the name given to the pure white KCl that can occur within the sylvinite seam (Fig. 8).

Various inclusions can be found within the potash seam. The most problematic being boracite, which occurs in the form of hard, insoluble nodules that can quickly damage the cutting heads of the machines. Therefore, we try to avoid mining in areas with high boracite content.

The sylvinite is overlain by a very weak carnallitic marl. This gives great problems in controlling the mine roof if we get too close to it and so we leave 2m of sylvinite in the roof to ensure the stability of the workings.

In theory the potash seam should extend all the way across the North Sea. The Germans are working the same seam on the other side. However, as we have seen, the presence of carnallite and boracite, and the very variable thickness and grade of the sylvinite means that we need an extensive drilling programme to identify the best areas to work economically.

Polyhalite is a modified anhydrite found some 150m below our normal working horizon. It has the formula $K_2SO_4.MgSO_4.2CaSO_4.2H_2O$. This rock is much stronger than sylvinite and can be mined at greater depth. It forms a good natural fertilizer and may well be the future of the mine.

Figure 8 Sylvinite rock.

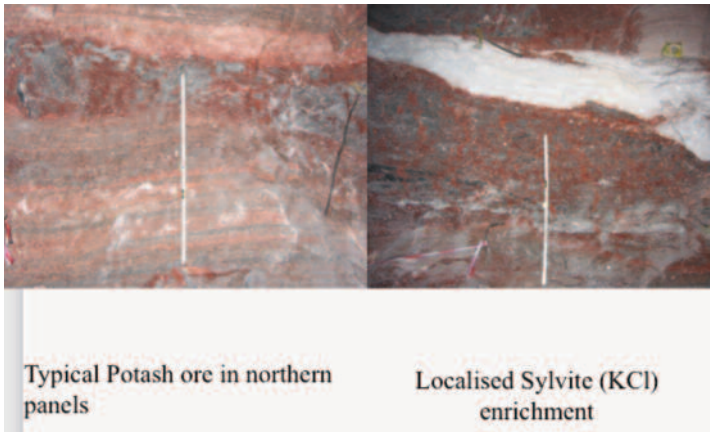

Figure 9 Exploration boreholes in the north section of the mine.

The general dip of the strata is from north-west to south-east. Depth to the potash at the shafts is 1,100m. In the northern mining areas it is 800m and in the south 1,350m.

The geothermal gradient is steep in this area and this gives a rock temperature of 45–46˚ C in the deeper parts of the mine. Humidity is low due to the halites absorbing the moisture in the air as it flow through the mine.

Exploration

Each year Boulby drills 100km of horizontal exploration holes. Each hole is *c.* 2km long. The holes generally start in the salt below the potash, but are deflected up at intervals to take sections through the potash seam. After each section is finished, a borehole survey is completed to ensure that the exact location of the section is known. All holes are fully cored using reverse circulation of saturated brine to flush the cores out of the tail end of the drill string. The drillers lay the cores out on corrugated sheets for later examination by the geologists, with samples being sent for laboratory analysis to determine grade (Fig. 9).

Much offshore seismic work has also been completed to give a comprehensive picture of the geological structure.

Figure 10 Joy Continuous Miner.

Mining

The standard machine that we use to excavate the various minerals is the 'Continuous Miner'.

These machines weigh approximately 100 tonnes and a new one currently costs more than £3 million. The mine operates a fleet of 10 or 12 of these machines. They are electrically powered, operating on 3.3KV and are remotely controlled by an operator who stands some 20m away (Fig. 10).

The machines cut tunnels 3.8m high and 8m wide. The rock that is excavated is loaded by the continuous miners into shuttle cars, which transport the mineral to the conveyor belt, which is usually maintained to within a distance of 100m of the face.

In the potash seam the production layout is a modified room-and-pillar system, but with surprisingly narrow pillars, which yield, encouraging the roof beam to flex in the critical areas rather than to break. Reinforcing bolts 1.5m long are used systematically to add strength to the roof beam. Movement of the roof is continuously monitored using 'tell-tale' extensometer stations. Should an area be seen to be in danger of failing, additional steel and timber supports will be set to stabilise the roadway.

A 2m beam of good potash is maintained in the roof to avoid roof collaspse due to the weak carnallitic marl above. This is controlled by the geologists, who probe forward after each 8m cut inserting a gamma radiation sensor into a small-diameter drill hole. Each of the different minerals encountered emits differing amounts of gamma and so the geologist can build up a picture of the strata immediately ahead of the working face and apply grade lines accordingly to keep the working face a safe distance below the marl.

Because of the high closure rates within the potash workings, two roadways are advanced into each area of the mine in the more resilient salt horizon *c.* 10m below the potash. This is done by a second machine and crew to form the long-life infrastructure roadways of the mine. When the potash roads have deformed to such an extent that it is no longer economical to maintain them, they are abandoned and sealed off. New potash districts are then developed from the salt roadways (Fig. 11, *opposite*).

Each machine is operated by a team of approximately 10 people. The overseer is in charge of both safety and production. He will usually have a fitter and an electrician and six or seven men to operate the machines. Shifts are 9.5 hours long and the crew work a cycle of two day shifts, two afternoon shifts and two night shifts followed by four days off. In this way the machine can be kept running 24 hours a day seven days a week. Two-day maintenance periods are scheduled into the programme and the production crew will be redeployed to an alternative district while the specialist maintenance crew ensures that the machines are serviced and repaired.

The six or so potash production districts are located in different areas of the mine so as to give more chance of producing an even grade once the products from the different districts are blended together on the conveyor belts. The farthest production panels are currently operating at a distance of more than seven miles from the shafts.

As with all mines, there are hazards that need to be controlled. Particularly important at Boulby is the potential to mine into pockets of high-pressure gas. If this occurs, then the resultant discharge can result in several hundred tons of rock being ejected along with a variety of gasses, including methane and the higher hydrocarbons. Such areas of potential outburst can, to some extent, be predicted by the geologists, and in such areas a modified mining procedure is employed that relies on removing personnel from the danger area while cutting is taking place. Large ventilation quantities are generally able to quickly dilute gasses emitted, but in such circumstances additional oxygen sets are available to the crews should they be needed.

Water is another potential hazard and the design of the mine is such that rock mechanics stresses on the aquifer should not be high enough to promote water ingress. The great majority of the mine is desert-like in its dryness but there are a few places, usually associated with fault planes that make significant quantities of water. Almost 1,000 gallons of water per minute are continuously pumped out of the mine.

Polyhalite

There would appear to be very extensive reserves of polyhalite accessible within the current mining area. Two access drifts were driven from the northern part of the mine into the polyhalite in 2010. Trial workings have been progressing steadily since then gathering information on consistency of grade, machine suitability and roof support.

The current world market for this material is small, but the potential is great.

It is expected that production will increase quickly as the customers become acquainted with the product and we learn the most efficient ways to mine it.

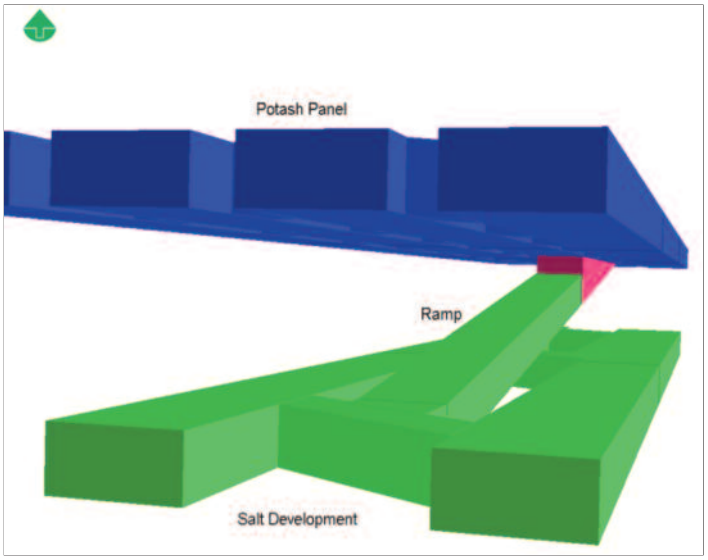

Figure 11 The relationship between the potash and salt roadways.

Conclusion

Boulby is a fascinating mine with many challenges, but also with many years of experience in how these challenges can be overcome. The availability of salt, sylvinite and polyhalite within the mining area gives some flexibility to help cope with changing world markets in years to come.

This has been just a lightening tour of what goes on at the mine, but hopefully you will have learned a little of the many skills and professions that are needed to operate a large mine.

Any views expressed in this talk are those of the author and do not necessarily represent the views of the Company.

Book review

Misra, Achyuta Ayan, and Mukherjee, Soumyajit 2015 *Tectonic Inheritance in Continental Rifts and Passive Margins*. Cham, Heidleberg, New York, Dordrecht, London: Springer (ISBN 978-3-31920-575-5; paperback, xii + 88pp; €51.99, Amazon price £34.37; ebook €41.64)

Misra and Mukherjee are in the Department of Earth Sciences at the Indian Institute of Tehnology, Mumbai (Bombay). Both are accomplished authors in the field of continental plates and plate margin geology, especially Soumyajit Mukherjee.

Tectonic Inheritance is one in a series called 'Springer Briefs in Earth Sciences'. Springer's website [accessed 15-1-16] lists 44 titles in the series, ranging from 'general' geological topics such as this one to specific past geological event and region titles. All are at this or a similar price, so assumed to be similarly 'brief'.

Tectonic Inheritance has seven brief chapters:

1 Introduction (1–6), which describes the subject matter, including informative cartoons and a map (Fig. 1.3) of the rift systems and passive margins discussed in detail in the book.
2 General Aspects (7–8), which, although curiously also the title of the first subsection of the Introduction, principally defines what the authors mean by 'inheritance'.
3 Influence of Pre-existing Anisotropics on Fault Propagation (9–20), which begins to get into the real 'meat' of the subject. There are several numbered formulae, and many technical diagrams and cartoons.
4 Pre-existing Fabrics (21–52), which describes and discusses the eight rift systems and margin zones shown on the map in the Introduction. These range around the world and include all the continents except Antarctica. There are 24 well-drawn, complex and useful maps, diagrams and schematics, many in colour. The rift systems and margin zones included are divided into 'Pervasive Fabrics' and 'Discrete Fabrics' (in both of which some zones are discussed): the East African Rift System (zone 5 on Fig. 1.3 map), the Thailand Tertiary Rift System (zone 8), theSouth Atlantic Passive Margins (not actually figured on the map), the East and West Indian Passive Margins (zones 6 & 7), the Brazilian Rifts (zone 2), the North Atlantic Passive Margin (zone 3), the Eastern North American Rift System (zone 1), and the Rhine Graben (zone 4).
5 Role of Lithosphere Rheology on Rift Architecture (53–60), which discusses 'extensional geodynamics', 'lithospheric strength', and 'temperature and strain rates'. This chapter is technical but free of formulae, and includes several detailed and complex 'modelling prediction diagrams' and comparative 'correlation illustrations'.
6 Lessons from Analogue Models (61–2), self-evidently, discusses issues, accuracy and the predictability of models.
7 Summary (63–5) The summary and opening Abstract (xi–xii) make similar points, although they also complement each other, and the summary mentions the zones studied.
An **Appendix** on page 67 is a technical explanation of 'effective elastic thickness', 'lithospheric strength profiles' and 'thermal age', with a rock diagram.

Multiple citations are frequent throughout the book on almost every topic mentioned; the authors are clearly well read. However, there are sometimes so many citations within a given sentence that the actual text is hard to follow. The References at the end occupy 18 pages — comprising 20.45% of the book.

There is a two-page **Index**, mostly of place names rather than of subjects.

Despite its short extent, this is a technically challenging book. The text is specialised. It is not a book for geology 'first years', but is a useful resource for discussions of some of the famed rift systems and plate margin zones around the globe; and the extensive reference list provides a good place for keen students to pursue further detail.

Finally, although unlikely, unless there is an error on the Springer website and/or on the Amazon page, the price of this book is exorbitant for an 88-page book, even if a most technical and informative one. Springer does not appear to publish anything other than books of this nature and pricing.

— David M. Jones, BA Hons (UC Berkeley), MA (Inst Archeeol London), PhD (UC London), BSc Hons (Open), OUGS Proceedings Editor

The history of Permian geological investigation in north-east England

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Background

Recorded investigations into the geology of the area we now know as the Permian of north-east England begin around the end of the 18th century, but I will begin my story back in antiquity in the Mediterranean. The region of Thessaly on the east coast of Greece has historically been a source of the mineral known as lodestone. Its natural magnetism made it a valuable commodity. According to Greek mythology, part of Thessaly was ruled by Magnes, one of the sons of Zeus. The region he governed was called Magnesia and his subjects the Magnetes (Fig. 1). It is from this that the name magnet is derived and also the mineral magnetite. In addition to lodestone there were two other minerals from the region that were of value. Together these minerals were known as *Magnitis lithos* or 'stones of Magnesia'. One was a black mineral used in glass-making and was called *Magnesia nigra* (pyrolusite), the other a white mineral used as a cosmetic and called *Magnesia alba*; the latter also had another name, *Magnesia carneus* ('flesh magnet'), because of the way it would stick to the lips.

Another property of *Magnesia alba* was that it appeared to be beneficial to health. At the start of the 17th century a compound known as Conte di Palma's powder was being sold by the Roman Count Di Palma as a panacea. He kept its source a closely guarded secret, but in 1707 the German physician Michael Bernhard Valentini (1657–1729) revealed that it was *Magnesia alba* and described a process for its manufacture (Fig. 2).

Figure 1 'Thessalia in Greece' by TUBS — redrawn by author. (This vector graphics image was created with Adobe Illustrator. The file was uploaded with Commonist, and the vector image includes elements taken or adapted from this source: Greece location map.svg (by Lencer). Licensed under CC BY-SA 3.0 via Commons: https://commons.wikimedia.org/wiki/File:Thessalia_in_Greece.svg#/media/File:Thessalia_in_Greece.svg).

In 1722 another German physician, Friedrich Hoffmann (1660–1742; Fig. 3, *overleaf*), described its medicinal effects and reported on the properties of *Magnesia alba* in his book *Observationum physic-chymicarum*. One of his key observations was that it did not effervesce with the application of dilute acid.

The story now moves to Britain where the Scottish physician and chemist, Joseph Black (1728–1799; Fig. 4, *overleaf*) wrote a thesis on experiments on *Magnesia alba*, which was published in 1756 in the journal *Essays and Observations, Literary and Philosophical*. As it was a medical thesis he covered its curative properties, but he also looked into its chemical properties. He referred to Hoffman's earlier work and verified the latter's findings. In addition, he carried out a number of experiments comparing *Magnesia* with lime. His conclusion was that as it had many properties that differed: *Magnesia* was not simply another calcareous earth, but must be a compound of a different element — a carbonate of *Magnesia*. Black is now credited with the discovery of magnesium along with that of 'fixed air' (carbon dioxide). He also went on to propose the idea of latent heat.

Figure 2 'Michael Bernhard Valentini' (artist unknown; http://ihm.nlm.nih.gov/images/B25184. Licensed under Public Domain via Commons: https://commons.wikimedia.org/wiki/File:Michael_Bernhard_Valentini.jpg#/media/File:Michael_Bernhard_Valentini.jpg).

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Figure 3 'Friedrich Hoffmann' by Johann Georg Wolfgang — http://www.sil.si.edu/digitalcollections/hst/scientific-identity/CF/display_results.cfm?alpha_sort=h. Licensed under Public Domain via Commons: https://commons.wikimedia.org/wiki/File:Friedrich_Hoffmann.jpg#/media/File:Friedrich_Hoffmann.jpg).

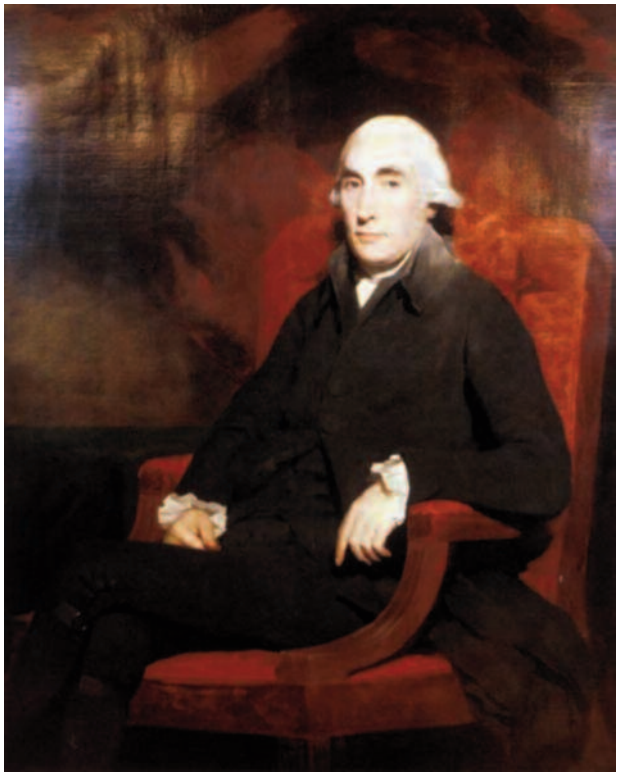


Figure 4 Joseph Black (© The University of Glasgow; without further permission, you may access, download and/or print contents for non-commercial private research and study purposes).

Figure 5 'Deodat de Dolomieu' by Déssiné d'apres le Portrait par M. Cordier, gravé par Ambroise Tardieu — http://ihm.nlm.nih.gov/images/B06032. Licensed under Public Domain via Commons: https://commons.wikimedia.org/wiki/File:Deodat_de_Dolomieu2.jpg#/media/File:Deodat_de_Dolomieu2.jpg).

Early investigations in north-east England

Having established that *Magnesia alba* is magnesium carbonate the story moves back to the continent and to France where the aristocrat Déodat de Dolomieu (1750–1801; Fig. 5), having had a military career from the age of 12, became a member of their Royal Academy of Sciences. His main interests were mineralogy, volcanoes and mountain formation and he went on many scientific excursions throughout Europe, collecting minerals. On his travels he had noted that among the ancient marble statues of Rome there were many that had suffered corrosion from the forces of nature, but others seemed to be more resistant to erosion. These were made of a hard Greek marble, which he noted effervesced little in acid. In 1791 he wrote about a tour he made of the Tyrolean Alps, where he discovered 'calcareous' rocks with similar properties to the Roman statues (*Observations et Memoires sur La Physique*). This stone was hard and did not effervesce with acid. He also noted rhombic crystals within cavities in the rock. The following year Nicolas-Théodore de Saussure named the rock Dolomite after Dolomieu. The major mineral constituent is also called dolomite ($CaMg(CO_3)_2$) and the mountain region is named the Dolomites.

At this time the rocks in the Durham coast area had been little studied as, unlike the nearby coalfields and north-Pennine orefield, they had little economic value. There is evidence that Iron Age farmers knew that crops grew better on what we now know to be magnesian grassland than on other areas. The Romans used the stone for building places like Arbeia (South Shields, AD 120; Fig. 6, *opposite*), and it was used in the building of York Minster (1230) and the Newcastle Exchange building (1658). It also found use in the construction of more industrial buildings such as

Figure 6 'Arbeia Roman Fort reconstructed gateway' by Chris McKenna (Thryduulf) (licensed under CC BY-SA 4.0 via Commons — https://commons.wikimedia.org/wiki/File:Arbeia_Roman_Fort_reconstructed_gateway.jpg#/media/File:Arbeia_Roman_Fort_reconstructed_gateway.jpg).

Whitburn Mill (1790) and local limekilns. This last use indicates its other use as a fertiliser, following calcination. There are documents recording leases for quarrying for this purpose at Marden (Whitley) Quarry dating back as far as the 1650s.

It was reports relating to the agricultural properties of this 'lime' that initiated the first in-depth study of the Durham rocks. Durham doctor, magistrate and landowner John Ralph Fenwick (1761–1855) wrote an 'Essay on Calcareous Manures' in the *Annals of Agriculture* (1794) in which he says that his farmers were aware of two kinds of lime in the area, a 'hot' kind and a 'mild' kind. The hot one had to be used sparingly, otherwise crops would not grow. This came to the attention of chemist Smithson Tennant (1761–1815), who carried out a number of agricultural experiments with the two types of lime, and in his paper, 'On different Sorts of Lime used in Agriculture' in the *Transactions of the Royal Society* (1799), noted that the hot lime contained two parts magnesia to three parts calcareous earth. He named this lime 'Magnesian Limestone' and said it could be easily identified by its slowness to dissolve in acids. He also suspected that Dolomieu's marble called Dolomite was probably of a similar composition. Tennant went on to become Professor of Chemistry at Cambridge and discovered Osmium and Rhenium.

About the end of the 18th century many Literary and Philosophical Societies were appearing around the country. Newcastle's was founded in 1793 as a 'conversation club', in which the only things off limits were politics and religion. It also held a collection of natural history items and many local naturalists were among its membership. These 'amateurs' were responsible for much of the early exploration of the newly named Magnesian Limestone. Their findings were reported in both local and national publications, and they often provided material for more notable naturalists. One such recipient was James Sowerby (1757–1822), the father of a dynasty of naturalists and illustrators. Among his publications were articles on botany, fungi and conchology, but it is in his *British Mineralogy* (Vol. 1, 1804) that we find the first illustration of specimens from the Magnesian Limestone (Fig. 7). The specimens were collected from the Sunderland area by local collectors and include the remarkable botryoidal form that he calls *Calx carbonata, foetida*, which he reports is found from Sunderland down as far as Hartlepool. Note that this is recorded as a calcium carbonate rather than as magnesian. The first sketch of a fossil from the area appears in volume three of his mineralogy (1809) and is listed as *Calx carbonata, magnesiata*. In the intervening years Humphry Davy had isolated the element from *Magnesia alba*, which he called Magnium (1807); it was later renamed Magnesium. The element from *Magnesia nigra* had been called Manganesium, which also was renamed to Manganese.

It was about this time that William Smith (1769–1839) was undertaking his mapping of the strata of England and Wales. Geology was still in its infancy and one man responsible for

Figure 7 'Sketches of botryoidal and spherical forms of Concretionary Limestone' by J. Sowerby (1804 British Mineralogy ***1****; Biodiversity Heritage Library: out of copyright).*

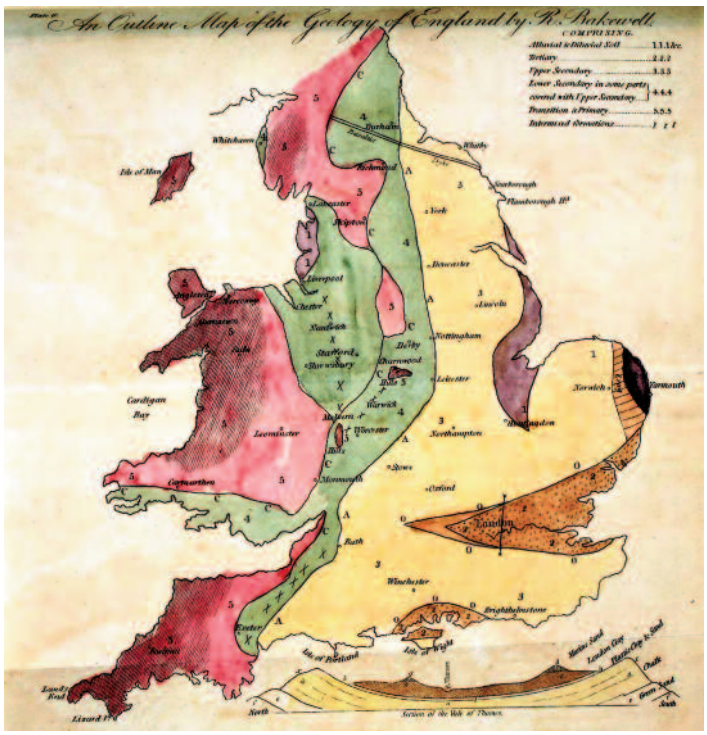


Figure 8 'Outline Map of the Geology of England' by R. Bakewell (1813 Introduction to Geology*; Biodiversity Heritage Library: out of copyright).*

helping to spread knowledge on the subject was Robert Bakewell (1768–1843). From 1811 he toured the country lecturing on geology and showing illustrations of maps and sections on the rocks. His *Introduction to Geology* (1813) is regarded as one of the earliest textbooks on the subject (it went on to have five editions) and includes a brief mention of the Magnesian Limestone of Durham. It included an early map of the geology of Britain, which divided the rocks into Transition and Primary, Lower Secondary, Upper Secondary, Tertiary and Alluvial and Diluvial. His boundary between Upper and Lower Secondary follows the western edge of the Magnesian Limestone reasonably well (Fig. 8).

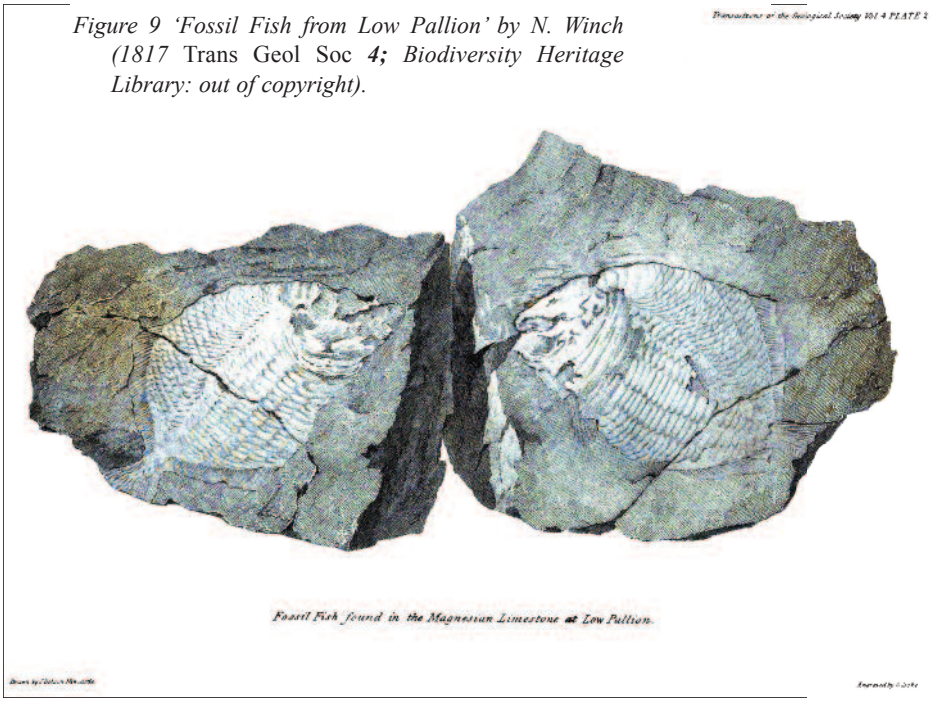
Much more detailed observations were the realm of the local naturalists. The most notable of these was Nathaniel John Winch

Figure 10 'Geological Map of Durham and Northumberland' by N. Winch (1817 Trans Geol Soc ***4****; Biodiversity Heritage Library: out of copyright).*

(1768–1838). He hailed from Middlesex but moved to the north-east in 1786 where, following an apprenticeship as a hostman, he ran a business as an iron merchant and anchor smith. He became bankrupt in 1808, possibly due to his indulgences in the fields of botany and geology. His paper 'Observations on the geology of Northumberland' (1817 *Trans Geol Soc* **4**) contained a lengthy description of the extent and nature of the Magnesian Limestone, including its northernmost exposures at Whitley Quarry. Significantly, his article included the earliest geological map of the district (dated March 1814) and also an illustration (by noted local surveyor and architect John Dobson) of the first fossil fish to be found within the Magnesian Limestone (Fig. 9). His map gave good detail of the western extent of the limestone, but its southern boundary was less distinct. This was probably partly due to the lack of exposure, but also, possibly, because of the difficulty in separating the upper beds from the overlying New Red Sandstone (Fig. 10). Winch had earlier provided some of the mineral specimens illustrated by Sowerby in his British Mineralogy.

Published slightly earlier than Winch's paper, but read a few months later (November 1814), was an article entitled 'A geognostical sketch of the counties

Figure 9 'Fossil Fish from Low Pallion' by N. Winch (1817 Trans Geol Soc ***4****; Biodiversity Heritage Library: out of copyright).*



of Northumberland, Durham and part of Cumberland' (*Annal Philos* **4**) by Scottish chemist and mineralogist Thomas Thomson (1773–1852). It also contained a map of the region, with far less detail but mentioned his visit to the area in August 1814 when he visited four hills. He gave the first report on the fossils of Humbledon Hill and the unusual limestone balls of Fulwell Quarry, as well as the results of his chemical analysis of the rocks. His article also includes the first mention of the so-called 'flexible limestone' of Marsden.

In the *Annals of Philosophy* (1815, **6**), Dr William Reid Clanny (1776–1850) of Bishopwearmouth gave an account of the 'Sunderland Limestone Formation'. He apologises to Thomson for not having taken him to Pallion lime-works on his visit of 1814 and goes on to give a detailed section through the rocks there noting layers with and without magnesia and those with fish fossils. He also reports the sinking of a shaft through the limestone in 1787 in search of coal, but no workable seams being found. Clanny invented a miner's safety lamp predating Davy's version. He was also Head Physician at Sunderland Infirmary in 1831 during the first outbreak of cholera in the British Isles and did much to help prevent spread of the disease.

The professional geolgists

It was, of course, also in 1815 that William Smith published his map of the Strata of England and Wales. This was less accurate than Winch's map with respect to the Magnesian Limestone, with both the western and southern limits ill-defined. Smith subsequently went on to produce more detailed maps on a county basis.

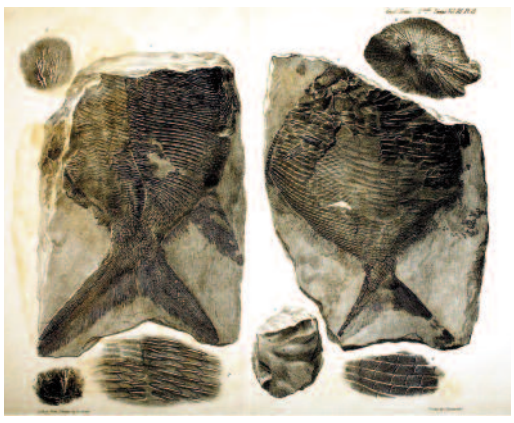
In the southern part of the district the width of the Magnesian Limestone placed the working coalfields some distance from the coast. About 1819 a committee chaired by John Fenwick was formed to discuss how to improve the movement of coal from the Durham coalfields to the port at Stockton. The possibility of a canal was suggested, but the committee finally settled on a railway for horse-drawn carriages. Approval was finally obtained in 1821, at which time George Stephenson became involved and convinced them to use steam-powered locomotives instead of horses. So began the building of the Stockton to Darlington Railway. It did not, however, stop at Darlington, as this was still some way from the coalfields. It continued north-west to Shildon on the edge of the coal measures (Fig. 11). Construction involved the opening of quarries to provide materials. Two such quarries were at East Thickley and Middridge, just east of Shildon.

During the summers of 1821, 1822 and 1823 Adam Sedgwick (1785–1873), then the Woodwardian Professor of Geology at Cambridge, visited the region to carry out fieldwork. On his way to the area in 1821 he stopped at Robin Hood's Bay. While hammering rocks in the bay he was hit in the eye by a splinter, leaving him virtually blind in that eye for the rest of his life. He continued with his trip and made visits to East Thickley and Middridge Quarries as well as meeting local naturalists, who provided him with specimens from their collections. Publication of his findings was not immediate, however. His papers were read at the Geological Society of London in 1826, 1827 and 1828, and were finally published in their *Transactions* in 1829 in an 88-page piece entitled 'On the geological relations and internal structure of the Magnesian Limestone'. In it he describes the formations within the Magnesian Limestone and draws similarities between it and formations on the Continent. This proved to be the most important work on the subject for over a century.

Figure 11 Plan of intended Stockton and Darlington Railway by The Committee of The Stockton and Darlington Railway — Report of the intended Rail or Tram Road from Stockton to Darlington 1821 (1821 Tracts ***57****, 252; Licensed under Public Domain via Commons: https://commons.wikimedia.org/wiki/File:Tracts_vol_57_p252_1821_Plan_of_intended_Stockton_and_Darlington_Railway.jpg#/media/File:Tracts_vol_57_p252_1821_Plan_of_intended_Stockton_and_Darlington_Railway.jpg).*

Between Sedgwick's visit and publication of his work two other publications appeared. In the *Annals of Philosophy* (1821, **1**), William Buckland's paper on the 'Structure of the Alps, and adjoining parts of the Continent' compared the Magnesian Limestone of England with the Elder Alpine Limestone, in particular he mentioned the oolitic concretions in both, with those at Sunderland being the size of a 'cannon-ball'. I have found no record of him visiting the area himself, so assume that he has based his description on communications from fellow geologists. That name has stuck and Sedgwick gave the same description in his paper. Of course, they are not oolites. When Smith's county map of Durham was published in 1824 both his western and southern boundaries for the Magnesian Limestone were disputed by Sedgwick. Sedgwick also included sketches of notable sections at Claxheugh and at Tynemouth, as well as plates of fish fossils from the Marl Slate at East Thickley and Middridge (Fig. 12). Some of these specimens were not identified by Sedgwick.

Figure 12 'Marl-slate fossils from Middridge and East Thickley Quarries' (Sedgwick, A. 1829 Trans Geol Soc Ser 2, ***3****, Pl 12; Biodiversity Heritage Library: out of copyright).*



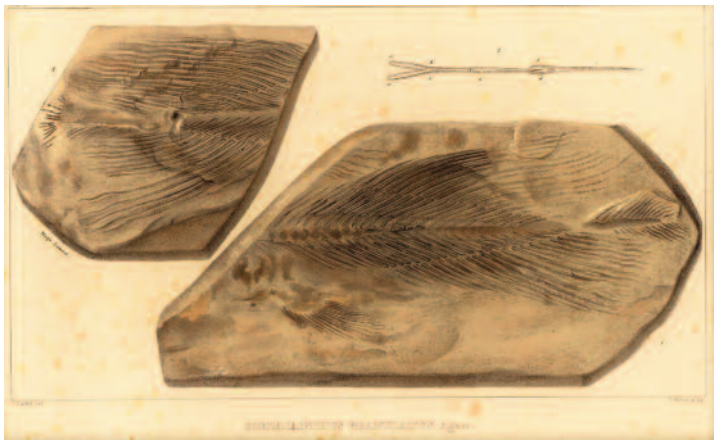


Figure 13 Coelocanthus granulatus *Agass (Agassiz, L. 1831* Recherces sur les Poissons Fossiles, vol. 1*; Biodiversity Heritage Library: out of copyright).*

Sedgwick passed on specimens to Swiss biologist and geologist Louis Agassiz (1807–1873). He had recently started working on fossil fishes, drawing up a new system of classification. His first volume of *Research on Fossil Fishes* (1833) includes a specimen from East Thickley, which he determined to be from a new genus which he called *Coelocanthus*, the world's first-discovered fossil Coelocanth (Fig. 13).

In 1841, following his expeditions in Russia, Roderick Murchison (1792–1871) determined that strata exposed in the region of Perm above the Carboniferous, although unlike the Magnesian Limestone in a similar position in England and Germany, these strata were of a new system, distinct from the New Red Sandstone. Murchison proposed the name of 'Permian System' to these rocks, and his geological map of England and Wales in 1843 is probably the first to depict the Permian System.

Newcastle Museum curators

The emphasis on research into the Magnesian Limestone now returned to local natural historians. In 1840 the Newcastle Museum found sufficient funds to employ its first paid curator. His name was William King (1809–1886), born in Sunderland and previously curator of what is now the Sunderland Museum, and he specialised in fossils from the Magnesian Limestone. An avid collector, he was helped enormously by the efforts of fellow collector, schoolteacher Richard Howse (1821–1901) of South Shields. Indeed, he frequently urged Howse to go out to key localities such as Tunstall and Humbledon Hills to collect specimens from the so-called 'shell-beds' to pass on to him. Through careful study of their anatomy he was able to describe many new genera and species, including a bivalve he named Bakevellia after Robert Bakewell, whose books on geology had inspired him from an early age. *Bakevellia* is now the name attributed to a Permian sea that formerly covered an area to the west of the Pennines with a fossil fauna rich in *Bakevellia*. King drew up a catalogue of the Permian fossils, which he presented to the Tyneside Naturalists' Field Club, which, at King's request, advertised it in the *London Geological Journal* (1847, **II**). In May of that year, however, King withdrew his catalogue from the printers without giving any notice to the Field Club. His actions may well have been in response to a dispute he was having with his employers. It transpired that King was selling Museum specimens, which he argued were his but which the Museum governors believed belonged to the museum collections on the grounds that King was employed by them as curator during the period in which the specimens were collected. This disputed resulted in King losing his job in November 1847, and appears to have been a blessing in disguise, for in 1849 King became a Fellow of the Geological Society of France and later, with a reference from Charles Lyell, was appointed to the Chair of Mineralogy and Geology at Queen's College, Galway, Ireland. In 1850 he produced his most noted publication, *A Monograph of the Permian Fossils of England*, with sketches by G. B. Sowerby (Fig. 14). His other claim to fame is that after examining bones discovered in the Neander valley, Germany in 1856, he determined that they were different from those of modern man and propose the name *Homo neanderthalensis* for this new species.

On the departure of King from the Newcastle Museum Richard Howse was appointed its new curator. His first task was to produce a catalogue of the Permian fossils for publication — the Field Club felt obliged to publish one as it had advertised one. They knew Howse had extensive notes and specimens on the subject and he was willing to oblige. In due course his *Catalogue of the Fossils of the Permian System of the Counties of Northumberland and Durham was advertised in the Newcastle Chronicle* of August 11, 1848 and published on 17 August 1848. As soon as the advertisement appeared King rushed his catalogue back to the printers to have it published privately. He did not wish to lose priority over the naming of new species, many of which had come from Howse' collection. His efforts were in vain however, as Howse' catalogue appeared two days before that of King's. Both were overshadowed by King's

Figure 14 Plate III from W. King 1850 The Permian Fossils of England *(author scan).*

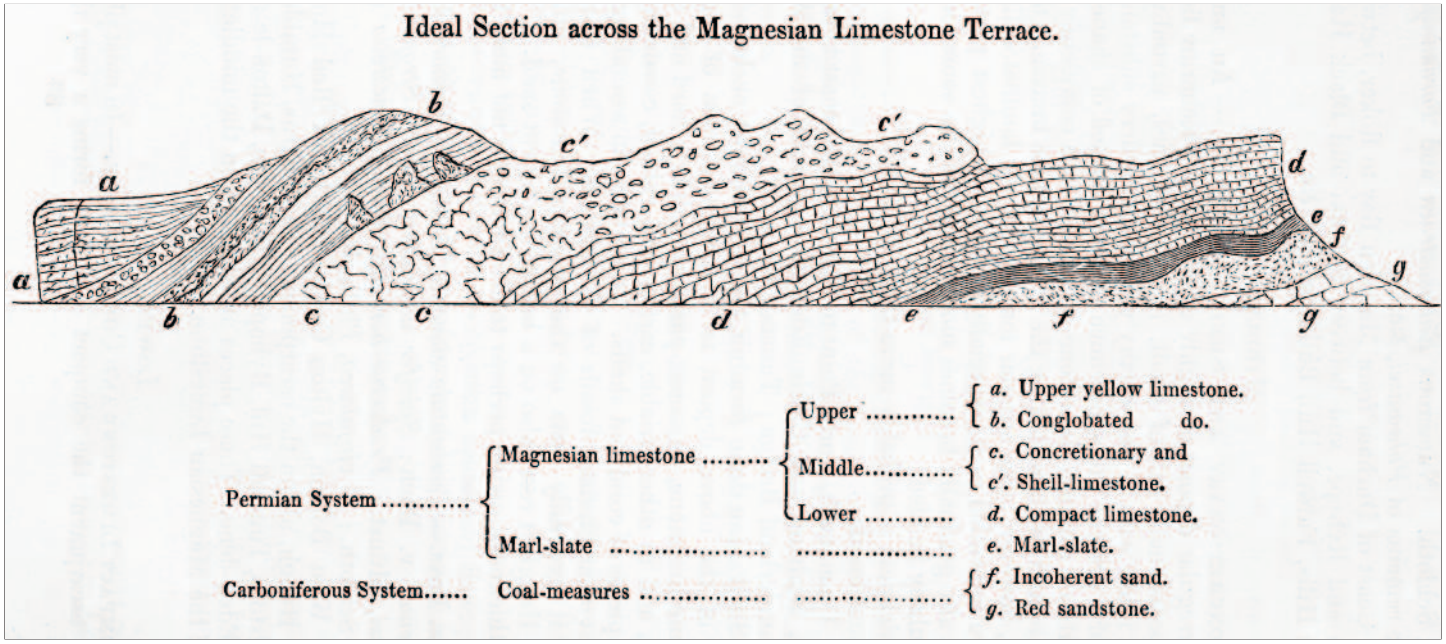


Figure 15 'Section across the Magnesian Limestone' (Howse, R. 1857 Annals and Magazine of Natural History*; Biodiversity Heritage Library: out of copyright.*

1850 monograph. Howse produced an update of his catalogue in 1857 addressing inaccuracies in earlier publications but also going to great length to prove his rite to priority over naming of species including correspondence from King regarding acquisition of specimens.

In the *Annals and Magazine of Natural History* (1857, **19**), Howse give a detailed description of the formations within the Permian and included a section across them (Fig. 15). At this point in time he included the Yellow Sands in the Carboniferous, and opinion that was challenged by Daglish and Forster in 1863 in their *Report for the British Association for the Advancement of Science*, in which they argued that the Yellow Sands were unconformable over the Carboniferous, but conformable to the overlying Magnesian Limestone. In another Tyneside Naturalists' Field Club Publication (*A Synopsis of the Geology of Durham*, 1863) Howse, along with fellow natural historian, James Kirkby (1834–1902) of Sunderland, reluctantly agreed to this placement of the Yellow Sands in the Permian.

Kirkby also made significant discoveries of new Chitons and Entomostraca within the shelly limestone at Humbleton Hill and found a new bed rich in fish fossils within Fulwell Quarry. This bed was somewhat higher than the Marl Slate and he termed it the Fulwell Fish-bed. In 1866 Kirkby, along with E. J. J. Browell published the first complete chemical analysis of the Magnesian Limestone Series in the *Transactions of the Natural History Society of Northumberland, Durham and Newcastle upon Tyn*e. They showed that the Ca:Mg composition varied from 96.94:1.66 to 42.48:49.86 with an absence of magnesia within the concretions.

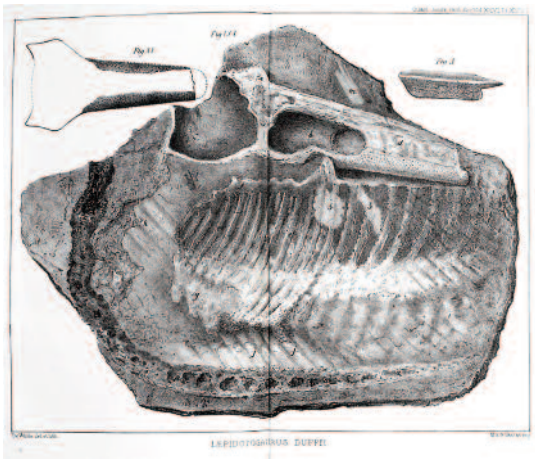
Further confirmation of the boundary between the Carboniferous and Permian was established by J. Clifton Ward (1843–1880) in 1869 in the *Quarterly Journal of the Geological Society (QJGS)* firmly placing the Rothliegende with the Millstone Grit in contrast to Sedgwick, Phillips and Murchison, all of whom placed the Rothliegende in the Permian. These publications helped define the western boundary of the Permian in the region.

In the late 1860s the railway at Shildon was being widened. This led to further fossil discoveries at Middridge Quarry by a local man, Joseph Duff, whose finds were reported by Howse and Albany Hancock (1806–1873) in the *QJGS* in 1870). Duff's finds included the first British specimens of teeth and skin from *Janessa*, a new Labyrinthodont, named *Lepidotosaurus duffi* (Fig. 16), another new species, named *Proterosaurus huxleyi*, and the first four British specimens of the fish *Dorypterus hofmanni*.

In 1871 Andrew Crombie Ramsay (1814–1891) — famous for his studies of the geology of Arran and other work — wrote about the pre-Triassic red rocks in the *Proceedings of the Geological Society*, arguing that the Magnesian Limestone could only have been produced by evaporation in a salt lake or inland sea, which, perhaps, had had a previous connection to the open sea. Up to this time the Magnesian Limestone had been thought to derive from erosion of magnesium-rich rocks.

By 1884 the Newcastle Museum had found a new home for its collections. Richard Howse was still the curator and was responsible for organising the new geological display at the Hancock Museum, St. Mary's Place, Newcastle upon Tyne (named after bothers John and Albany Hancock).

Figure 16 'Lepdotosaurus from Middridge Quarry' (Hancock A., and Howse, R. 1870 Quart J Geol Soc ***26****; Biodiversity Heritage Library: out of copyright).*



The academics

The College of Physical Science (now Newcastle University) had been established 1871 and in 1879 G. A. Lebour (1847–1918) became its Professor of Geology. His *Outlines of the Geology and Natural History of Northumberland and Durham* (1886) summarised the knowledge of the area, including his own findings. In it he comments on how Sedgwick's paper of 60 years earlier was still valuable. He reports that the Yellow Sands are always unconformable on the lower beds and, although non-fossiliferous, are undoubtedly Carboniferous. Like Sedgwick, he includes the sections at Claxheugh and Tynemouth (Fig. 17), and also describes the 'breccia gashes' at Marsden, and drew his own map of the Geology of Northumberland.

The following year Howse remarked, in the *Transactions of the Natural History Society of Northumberland and Durham* that the Yellow Sands were an inconsistent bed absent in places. He states that they comprise gritty, incoherent, strongly false-bedded sand likely to be of eolian deposition, the first time this had been suggested; Lebour supported this conclusion in his contribution to the *Victoria History of the County of Durham* (1905).

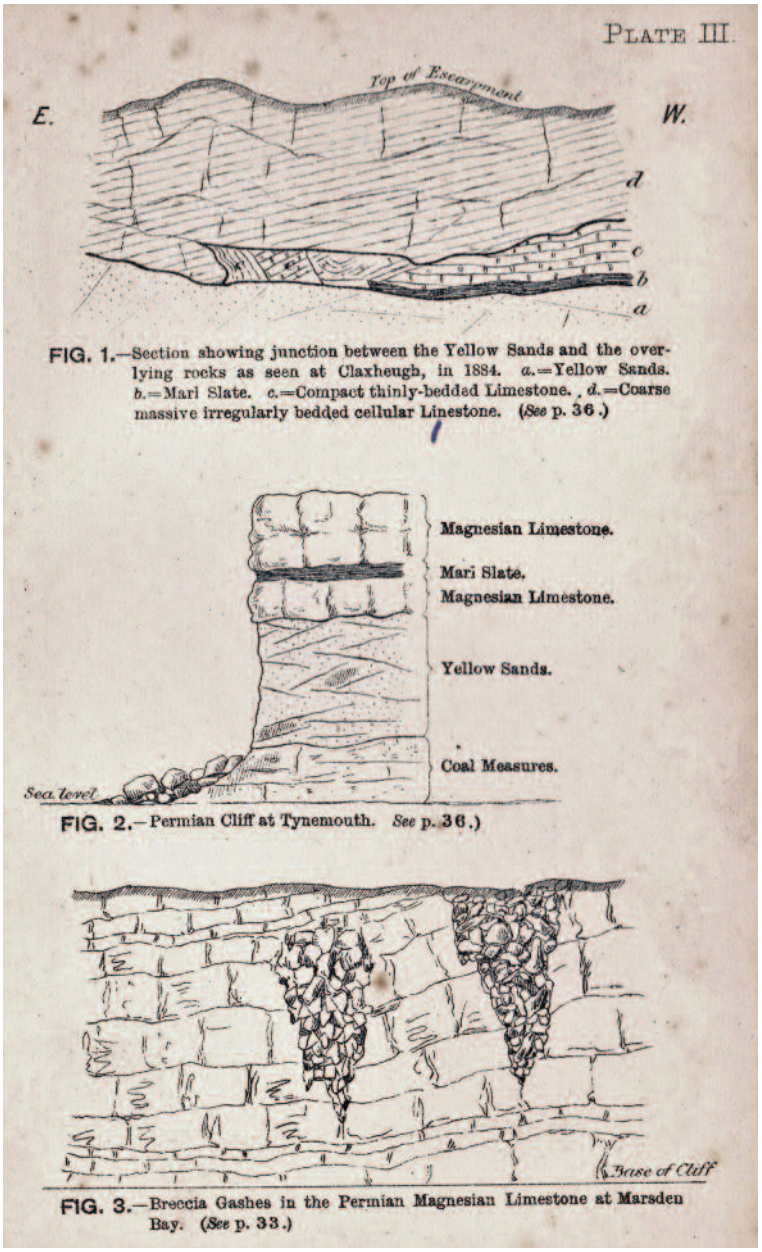


FIG. 1.—Section showing junction between the Yellow Sands and the overlying rocks as seen at Claxheugh, in 1884. *a.*=Yellow Sands. *b.*=Mari Slate. *c.*=Compact thinly-bedded Limestone. *d.*=Coarse massive irregularly bedded cellular Linestone. (*See* p. 36.)

FIG. 2.—Permian Cliff at Tynemouth. *See* p. 36.)

FIG. 3.—Breccia Gashes in the Permian Magnesian Limestone at Marsden Bay. (*See* p. 33.)

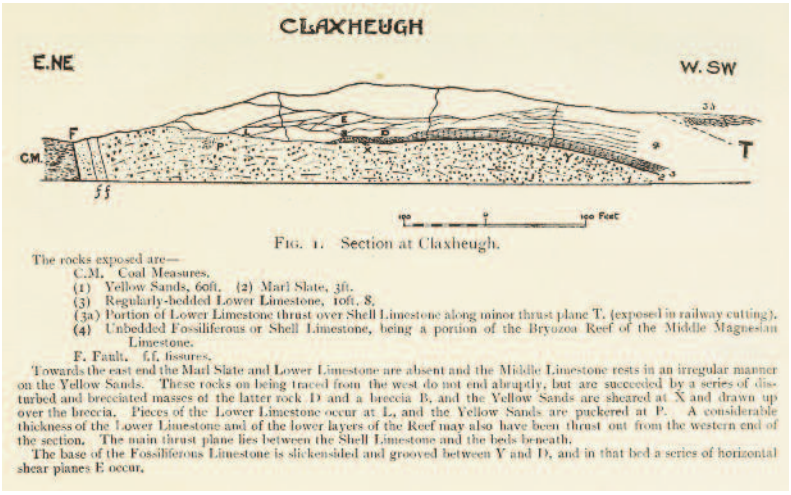


FIG. 1. Section at Claxheugh.

The rocks exposed are—
C.M. Coal Measures.
(1) Yellow Sands, 60ft. (2) Marl Slate, 3ft.
(3) Regularly-bedded Lower Limestone, 10ft. 8.
(3a) Portion of Lower Limestone thrust over Shell Limestone along minor thrust plane T. (exposed in railway cutting).
(4) Unbedded Fossiliferous or Shell Limestone, being a portion of the Bryozoa Reef of the Middle Magnesian Limestone.
F. Fault. f, f, fissures.

Towards the east end the Marl Slate and Lower Limestone are absent and the Middle Limestone rests in an irregular manner on the Yellow Sands. These rocks on being traced from the west do not end abruptly, but are succeeded by a series of disturbed and brecciated masses of the latter rock D and a breccia B, and the Yellow Sands are sheared at X and drawn up over the breccia. Pieces of the Lower Limestone occur at L, and the Yellow Sands are puckered at P. A considerable thickness of the Lower Limestone and of the lower layers of the Reef may also have been thrust out from the western end of the section. The main thrust plane lies between the Shell Limestone and the beds beneath.

The base of the Fossiliferous Limestone is slickensided and grooved between Y and D, and in that bed a series of horizontal shear planes E occur.

Figure 18 'Section at Claxheugh' by D. Woolacott (1918 Trans Nat Hist Soc Northumberland, Durham, and Newcastle upon Tyne*; Biodiversity Heritage Library: out of copyright).*

With much of the general complexity of the Magnesian Limestone in terms of its extent, upper and lower boundaries and depositional environment thus explained, research moved towards investigating some of the structural peculiarities. Former student of Lebour, David Woolacott (1872–1924), a lecturer at Newcastle, published many papers in the local Society Transactions between 1903 and 1919, and revised the classification of the Permian rocks. He was particularly interested in the sections at Claxheugh and Trow Point. He identified a thrust plane at Trow Point and suggested thrusting from the north. He used this to explain the sequence at Claxheugh with the Lower Limestone thrust over the Yellow Sands (not as Howse and Lebour had concluded years earlier), and also that the breccia gashes were caused by roof collapse into caverns where the shelly limestone had been removed (Fig. 18).

Woolacott was helped in his investigations by his friend, the eccentric 'amateur' geologist, C. T. Trechmann (1884–1964). Trechmann's family owned a cement works at Hartlepool, located on the Magnesian Limestone, and he had the means to carry out his own research. He travelled widely and while studying in Zurich in 1907 he became aware of reports of bryozoan reefs within the Permian rocks in Germany. He states that Woolacott was reaching the same conclusion regarding the so-called 'shell beds' in the Durham Permian. The sources of the fossils featured in Howse's and King's catalogues of 60 years earlier were part of this reef and included places such as the hills at Tunstall and Humbledon.

In the *Quarterly Journal of the Geological Society* (1913) Trechmann reported on a 265-foot thick mass of anhydrite discovered in a boring done in 1888 at the family's Warren Cement Works in Hartlepool. He determined that this lay within the Magnesian Limestone due to the fossils found in beds above and beneath it. Anhydrite of this thickness had not been found in other borings through the limestone, and he concluded that it had dissolved out elsewhere and that the dissolution of this great thickness was responsible for the subsequent collapse of the overlying beds, resulting in the collapse breccias as seen at Marsden (Fig. 19, *opposite*).

Figure 17 'Sketches of sections at Claxheugh, Tynemouth and Marsden' by G. A. Lebour (1886 Outlines of the Geology of Northumberland and Durham*; author scan).*

Woolacott revised his theories on the sections at Claxheugh and Trow Point and in the 1918 *Transactions of the Natural History Society of Northumberland, Durham and Newcastle* described the bryozoan reef and confirmed the unconformable relationship between the Yellow Sands and the Magnesian Limestone. He also corrected his explanation for the breccia gashes, but confirmed the existence of horizontal movements below the anhydrite layer at Claxheugh, Trow Point and Down Hill. This is now known to be due to a massive submarine slide within the Lower Limestone (Raisby Formation) called the Downhill Slide.

Trechmann continued to research and collect specimens until the 1930s and found several new fossil species from places such as East Thickley, but in his later years spent much of his life exploring the geology of the West Indies and of New Zealand. Little further work was done on these areas until the arrival of Denys Barker Smith (1929–2007) in the mid-1960s. Smith essentially rewrote the story of the Magnesian Limestone using all the earlier work outlined here, coupled with his own extensive research, which has earned him the title of 'Mr. Permian'.

My own investigations into the history of geological research in north-east England continue. I am still trying to determine by whom and when the term 'Zechstein Sea' was first used. In the early 1900s Lebour referred to the 'Permian Sea', but this name had been replaced by the Zechstein Sea by the 1960s. If anyone out there knows the answer I would be grateful if they could let me know (e-mail address after title).

Figure 19 'Anhydrite at Warren Cement Works, Hartlepool' (Trechmann, C. T. 1913 Quart J Geol Soc*; Biodiversity Heritage Library: out of copyright).*

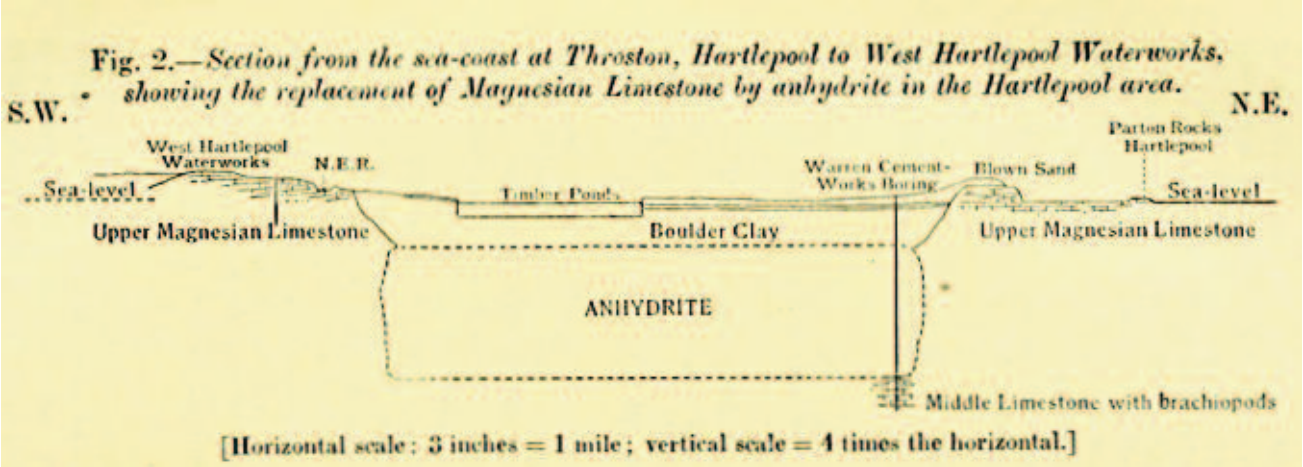


Fig. 2.—Section from the sea-coast at Throston, Hartlepool to West Hartlepool Waterworks, showing the replacement of Magnesian Limestone by anhydrite in the Hartlepool area.
S.W.
N.E.
West Hartlepool Waterworks
N.E.R.
Sea-level
Upper Magnesian Limestone
Timber Ponds
Boulder Clay
ANHYDRITE
Warren Cement-Works Boring
Blown Sand
Parton Rocks Hartlepool
Sea-level
Upper Magnesian Limestone
Middle Limestone with brachiopods
[Horizontal scale: 3 inches = 1 mile; vertical scale = 4 times the horizontal.]

Book review

Mason, John 2015 *Introducing Mineralogy*. Edinburgh: Dunedin Academic Press Ltd (ISBN 978-1-78046-028-4; paperback, 118pp; £14.99)

In his prologue to *Introducing Mineralogy* John Mason describes how he found a nugget of gold in a Welsh stream, which immediately drew me in and encouraged me to read the rest of the book. Who wouldn't want to be a mineralogist and find a nugget of gold?

Mason begins with a chapter on the basics of mineralogy, which is concise, readable and understandable, giving a crash course in the chemistry of the elements, including chemical bonding, crystallisation, crystal systems and the properties of minerals. He follows with two chapters on mineral occurrences, one describing rock forming minerals in igneous, sedimentary and metamorphic settings in the Earth's crust, together with meteorites from space, and rocks brought up from the mantle by geological processes. The other is on atypical occurrences where minerals are concentrated in higher proportions and the processes leading to such concentrations. Chapter 4 is about the dangers and ethics of mineral collecting, while Chapter 5 covers the study of mineral assemblages, including the use of petrography. Chapter 6 covers the minerals industry, the extraction of minerals from ore deposits and the uses minerals can be put to, both industrial and ornamental. Mason ends by looking at the environmental issues associated with mineral extraction, both detrimental, such as pollution, and beneficial, such as the place of minerals in soils.

There are copious colour illustrations of minerals, rocks and rocks in thin section. The few graphs and diagrams enhance the text, and there is a comprehensive glossary of defined terms whose first occurrences in the text are in bold blue. I found this at first a little off-putting, my eyes tending to skip over the blue words, but I got used to it.

The book is affordable, a good book for the beginner and will be of interest to those who already know something of mineralogy. I found his distillation of elemental chemistry masterly and will be glad to have it to hand if I ever have to explain it to my grandchildren.

— Suzanne Grain, MSc (Open), BSc Hons (Open), BA Hons (Wales)

Book review

Jones, Stuart J. 2015 I*ntroducing Sedimentology*. Edinburgh: Dundin Academic Press Ltd (ISBN paperback 978-1-78046-017-8; e-pub 978-1-78046-531-9; Kindle 978-1-78046-532-6; paperback and e-book; £12.99, Kindle edition £12.34.)

Dr Jones states at the beginning of the book, "this book is intended to provide some insight into sedimentology and the study of 'soft rocks' in different environmental settings and identify why sediments are so important" — a lot to squeeze into 86 pages. He begins with very simple explanations of how grains of rock are rounded and transported to the basins to be deposited as beds, before developing the concept of facies and sequence stratigraphy. I liked his sub-title — 'The hole in the ground to place the dirt' — when describing sediment deposition in basins; so down to earth!

Chapter two 'Sediment to sedimentary rock' begins with a flow diagram of the rock cycle followed by grain sorting. There follow photographs of various types of rock with brief descriptions of how they were formed.

Chapter three is about sedimentary structures and what they can tell us about how and where the rocks formed, as well as 'way up' in which they were deposited. This chapter is well illustrated with diagrams and photographs that illustrate the topic being discussed.

Chapter four discusses sedimentary environments that control the types of sediment deposited and the structures contained within them. For example glaciers pluck lumps of angular rock, which tend to form poorly sorted, coarse sediments close to the mountain front; whereas lakes deposit fine layers of mud and silt.

Chapter five is a short chapter about fossils and their use in determining past environments and the age of the rocks that contain them — biostratigraphy.

The final chapter is called 'The riches from sedimentary rocks' and covers everything from water to oil and gas.

Throughout the book, terms are highlighted and defined in the Glossary at the end; this is followed by a short list for further reading.

Although a short book, it packs a lot of information into a small space and still manages to explain the basic concepts. I liked the use of photographs showing sediments being deposited in present-day environments alongside photographs of similar rocks many millions of years older. The use of photographs with diagrams works very well. Some of the material is quite advanced, but it is introduced in a way that leads the reader in easy-to-understand steps. The other thing I liked is the list of illustrations with their pages at the beginning of the book.

This is a book that anyone with an interest in geology would find interesting, and for the more serious student it is a useful reminder and means of clarifying concepts.

Lyn Relph, BSc Hons (Open), BSc Hons (Bangor)

The Limestone Landscapes Project: linking the Permian geology to its landscape within a Landscapes Partnership Scheme

Tony Devos

Introduction

This paper describes the Limestone Landscapes Project. The author, along with other colleagues has been involved in this project since its planning and inception in 2007. The Landscape Partnership Scheme was completed at the end of 2015.

The Project is a landscape-scale initiative, and we have used National Character Areas as a coherent landscape scale. There are 159 National Character Areas in England. They are what Natural England uses to describe landscape — the areas are based on the geology, the ecology, the hydrology and the historic environment of a place. In the example of the Limestone Landscapes area, this is National Character Area 15, the Durham Magnesian Limestone Plateau (Fig. 1), the geology of which is the focus of this OUGS Symposium.

Figure 1 National Character Area 15, the Durham Magnesian Limestone Plateau.

The project uses Landscape Character Assessment; Durham County Council is particularly enthusiastic about this technique, and the Durham Council has encouraged the four other local authorities involved — Hartlepool, Darlington, South Tyneside and Sunderland — to use the same approach. This has given us a combined landscape character for the whole of the area, including the coast, the escarpment, the clay inlands and the limestone gorges cutting across them. In Figure 2 you can also see where the Magnesian Limestone outcrops.

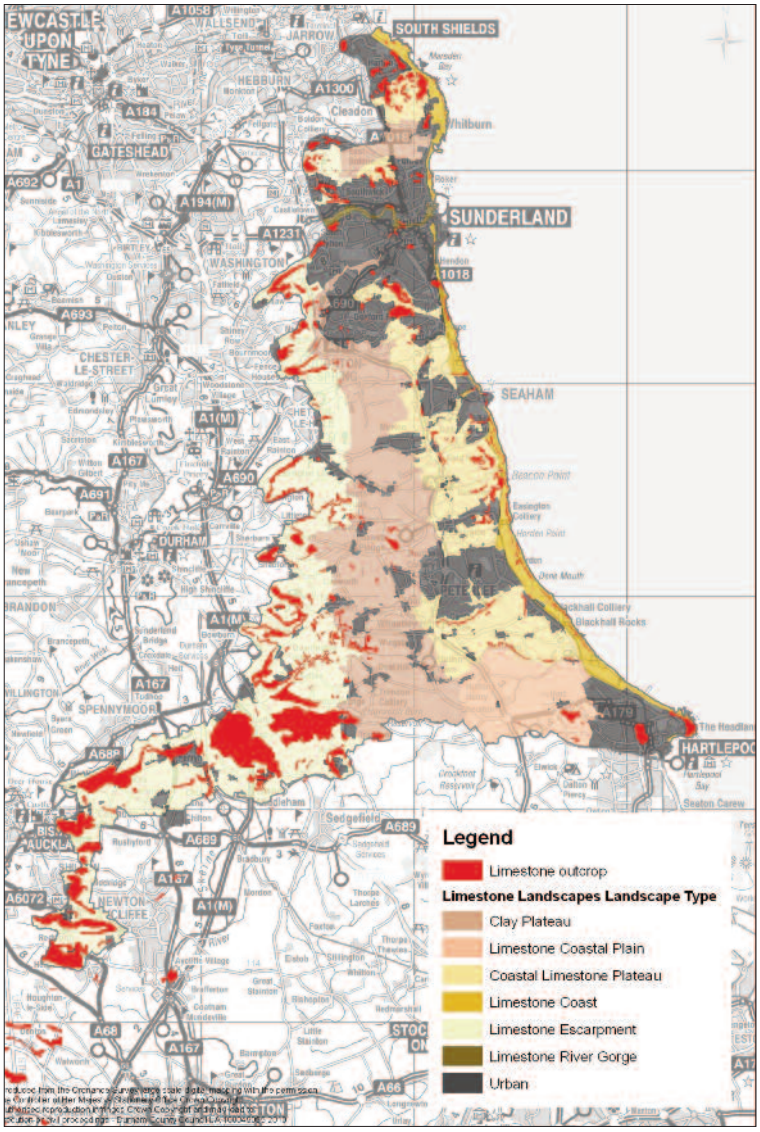
In terms of landscape, I don't mean just the view. The term includes the geology and soils, the biodiversity, the way in which it has been used in the past as well as the way in which we experience it today. These facets of landscape interact over time giving it its unique character.

Starting in 2007, it took three years to put together the funding bid for a Heritage Lottery Fund Landscape Partnership Scheme. The whole programme submitted was worth a total of £2.8 million: £1.9 million came from the Lottery Fund and other sources contributed £705,529 in cash contributions, plus £220,000 of in-kind contributions and volunteer time. Actually, we have had about £400,000-worth of volunteer time contributed, which has been significant in the delivery of the programme.

The Limestone Landscapes Partnership includes:

- the four local authorities (South Tyneside, Sunderland, Durham and Hartlepool),
- the Durham Wildlife Trust,
- the National Trust,
- the Grassland Trust (which unfortunately went into liquidation halfway through the project),
- Groundwork NE & Cumbria,
- the North of England Civic Trust, and
- a number of educational charities.

Figure 2 New Limestone character typology — limestone outcrops (shown in red) in the area defined in Figure 1.



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At the beginning of the project, the British Geological Survey carried out a geological audit of the area. This is now on the project website. The audit was followed by an 'Action Plan' of what would be delivered through the project. We produced a 'Historic Environment Audit and Action Plan', a 'Learning, Access and Community Engagement Plan,' and a 'Biodiversity Opportunity Mapping Plan'. These plans identified nearly £35 million-worth of projects, but given that the budget was only £2.8 million, we cherry-picked the easiest and most important of these. Our focus in prioritising was on preserving things that would be gone if we did not act now. Another important consideration was projects that were in 'friendly' land ownership and would be more likely to succeed and have the benefits maintained.

Geology-related projects were identified in many places right across the landscape, which you can see marked by stars on the Figure 3 map.

We split projects into a number of different objectives, derived from the Heritage Lottery Fund's criteria:

- conserving and restoring
- increasing access to, and learning about, geodiversity
- increasing community participation in the geology of the area
- developing training and skills

Figured 3 Map of potential site-specific geodiversity projects: geology-related projects (marked by stars) in the area defined in Figure 1.

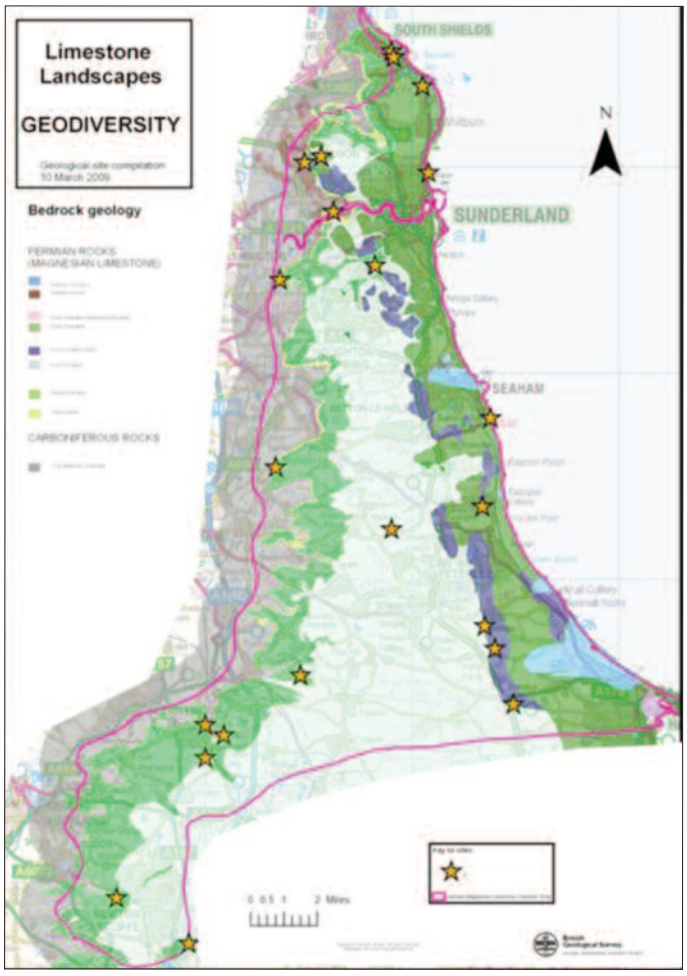


Figure 4 Carley Hill SSSI before any restoration work was started.

Conserving and restoring

There are three sites we have worked on. I think many of those who took part in the Symposium field trips will have visited some of them:

- Tunstall Hills and Ryhope Cut, which is part of the reef in the Sunderland area
- Marsden Old Quarry in South Tyneside
- Fullwell and Carley Hill quarries

The Fullwell and Carley Hill quarries are a geological SSSI, and as you can see in Figure 4 the site was not in a favourable condition at the start of the project. You could not get to it easily without a machete, and it was almost impossible to see anything of the special features of the area.

We spent a fair amount of money — about £35,000 — clearing the area, and bringing it back into favourable condition. We had people on ropes coming down from above to remove ivy and trees off the faces, as well as cherry pickers and bulldozers to level some parts of the area. This was necessary partly because there was a lot of anti-social behaviour on the site, especially in the woodlands. The exposure is now much more open (Fig. 5) and you can clearly see the strata including the Cannonball Rock (Fig. 6, *opposite*). We have also made visible some of the amazing patterns in the Concretionary Limestone. There are three faces in this exposure — east, west and north — all of which are now visible and accessible.

Figure 5 Carley Hill SSSI cliff face cleared, exposing the Cannonball Rock stratum (see Fig. 6, opposite).

Figure 6 Detail of the Cannonball Rock stratum at Carley Hill SSSI.

The exposure is world famous, and was described in this extract from the *Journal of Geology* in 1933: "… The forms of these structures are extremely varied and intergrown, producing what are probably the most remarkable patterns in sedimentary rocks found anywhere in the world." (Fig. 7)

The rationale for our work has been: "This exposure should be permanently preserved as one of the most outstanding examples of Nature's ability to build artistically in stone." Nature has certainly been up to that in the Fullwell and Carley Hill quarries area, as well as in places such as Hendon Beach.

Access and learning

We have also done a lot of access work. The first place we have done this is within the active quarries, from which rocks of the Magnesian Limestone are quarried to be used for refractory products, road stone and agricultural fertiliser. The underlying Permian Sands are also quarried for various uses. and I recently discovered that it is the only sand that is used on greyhound tracks!

We have put viewing platforms into the active quarries. The platform in Figure 8 *(overleaf)* is at Raisby Quarry near Coxhoe. We have also put in platforms at Thrislington Quarry, at Old Quarrington Quarry and at Cold Knuckles Quarry. Children and school parties use these sites extensively, and this is a good way to engage them with an important local industry, showing them what happens in these big holes in the ground.

They can have some fun, too. There is a 'fossil fishing' bay (Fig. 9, *overleaf*), which we put into the grounds of Cassop Primary School. The Marl Slate, which is a metre thick marker bed between the Permian Sands and the Magnesian Limestone contains a lot of fossil fish — including *Palaeoniscum*, *Pygopterus* and others (Fig. 10, *overleaf*) — and so we have a place in this school where children from around the area can go and crack open the Marl Slate to look for fossil fish. It is used by children of all ages, and it is usually the older ones that need to be chased out of it. There is even a fossil in Sunderland Museum that has a *Palaeoniscum* inside a *Pygopterus* (Fig. 11, *overleaf*).

At each of the viewing platforms (Fig. 12, *page 77*) and at the fossil fishing bay we have erected two information boards: one explains the Permian geology, the other explains what you can find at that site.

Over the past four years we have managed to engage with a large

Figure 7 Detail of the spherulite Concretionary Limestone at Carley Hill SSSI "...probably the most remarkable patterns in sedimentary rocks found anywhere in the world."

Figure 8 Raisby Quarry viewing platform.

number of children. We have had *[at the time of the lecture — Ed.]* 4,800 children from 203 schools looking at the geology of the area, using both live and former quarries; and 613 secondary school pupils from 12 schools.

We have also produced a series of five Geotrail leaflets (Fig. 13, *opposite*) as part of the *Trails and Tribulations Project*. These leaflets are available as hard copies and are also downloadable from the Limestone Landscapes website at http://www.limestonelandscapes.info/Pages/TrailsandTribulations.aspx. All the leaflets are well illustrated, and link the ecology, historic environment and the geology of the area.

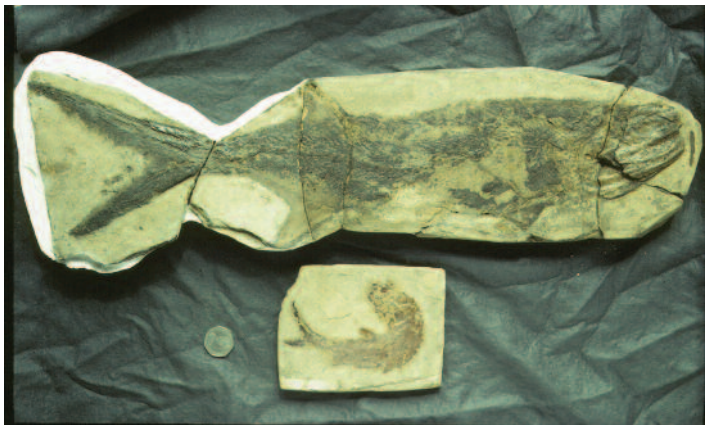
Figure 9 'Fossil fishing' bay at Cassop Primary School.

- The Geotrail in South Tyneside, *Cliffs, quarries and mills*, has a lot of information about the anhydrite dissolution, the Down Hill Slide, and the formation of the reef and other local Magnesian Limestone rocks.
- The *Rock in the city* leaflet covers the centre of Sunderland, based on a walk conducted by local geologist Andy Lane.
- *On top of the tropical reef* tells you about the *bryozoan* equivalent of the Great Barrier Reef, and this leaflet looks at the Tunstall Hills area where you can see the reef from the beginning of reef formation in the coquina all the way through to the top and the end of the reef.
- *Cliffs, caves and curious rocks* looks at a number of different rocks running down from the south side of Seaham in Dawdon to Hawthorn Dene. There are bits of reef and other rocks formed again through the Magnesian Limestone on the coast, along with the Easington Raised Beach.
- And last, *Coal, clay and quarries* features the back reef and the Permian Sands around Coxhoe, near some of the quarries there.

At the time of speaking we are just finishing a pair of interpretation boards in Mowbray Park, right in the centre of the city opposite the Civic Centre. These replace signs saying "Danger falling rocks" with "Danger! World class geology!" (Fig. 14, *page 78*), and act as signposts to the special Magnesian Limestone rocks from the heart of Sunderland City to elsewhere in the area.

There are a further three leaflets which look at the features of former quarries that are now used for recreation and nature conservation. These leaflets are part of the *Kingdom of Quarries* Project and can be found on the Limestone Landscapes website at http://www.limestonelandscapes.info/Pages/KingdomofQuarries.aspx

Figure 10 Fossil fish from the Marl Slate: Pygopterus *(above) and* Palaeoniscum *(below).*



- *Fulwell Quarry* looks at the Concretionary Limestone again, and links it to a World War I 'acoustic mirror', which we have just restored in the Quarry. Acoustic mirrors — a pre-cursor of radar — listened for Zeppelins, as there was a problem in Sunderland (one of the major ship building areas) with Zeppelin bombing during World War I. As soon as this acoustic mirror was installed it put a stop to the bombing because its warning gave pilots 15 to 20 minutes extra time to

Figure 11 Fossil fish from the Marl Slate: tail of Palaeoniscum *inside the body of a* Pygopterus.

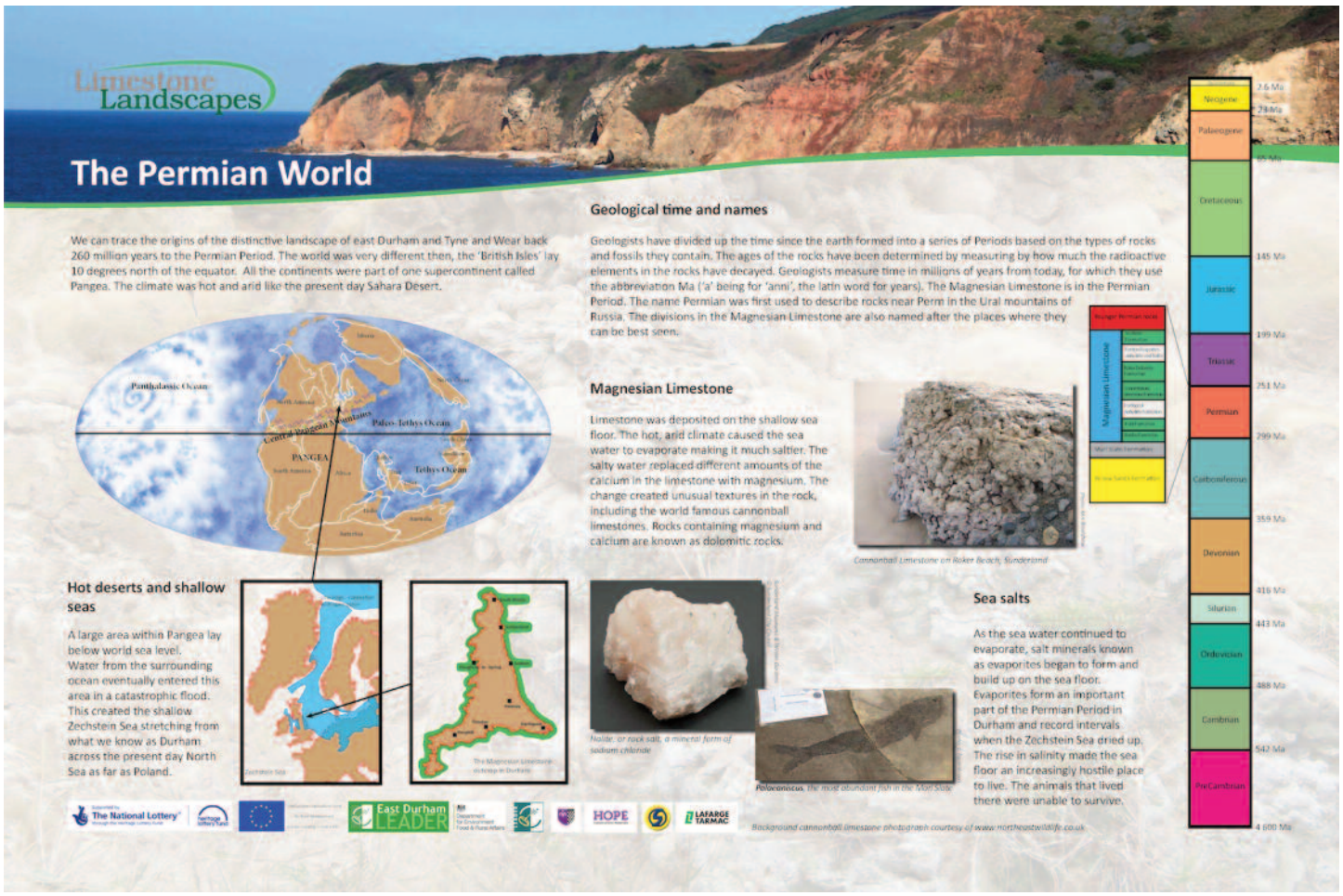

Limestone Landscapes
The Permian World
We can trace the origins of the distinctive landscape of east Durham and Tyne and Wear back 260 million years to the Permian Period. The world was very different then, the 'British Isles' lay 10 degrees north of the equator. All the continents were part of one supercontinent called Pangea. The climate was hot and arid like the present day Sahara Desert.
Geological time and names
Geologists have divided up the time since the earth formed into a series of Periods based on the types of rocks and fossils they contain. The ages of the rocks have been determined by measuring by how much the radioactive elements in the rocks have decayed. Geologists measure time in millions of years from today, for which they use the abbreviation Ma ('a' being for 'anni', the latin word for years). The Magnesian Limestone is in the Permian Period. The name Permian was first used to describe rocks near Perm in the Ural mountains of Russia. The divisions in the Magnesian Limestone are also named after the places where they can be best seen.
Panthalassic Ocean
Central European Mountains
Paleo-Tethys Ocean
PANGEA
Tethys Ocean
Magnesian Limestone
Limestone was deposited on the shallow sea floor. The hot, arid climate caused the sea water to evaporate making it much saltier. The salty water replaced different amounts of the calcium in the limestone with magnesium. The change created unusual textures in the rock, including the world famous cannonball limestones. Rocks containing magnesium and calcium are known as dolomitic rocks.
Cannonball Limestone on Roker Beach, Sunderland
Hot deserts and shallow seas
A large area within Pangea lay below world sea level. Water from the surrounding ocean eventually entered this area in a catastrophic flood. This created the shallow Zechstein Sea stretching from what we know as Durham across the present day North Sea as far as Poland.
Halite, or rock salt, a mineral form of sodium chloride
Palaeoniscus, the most abundant fish in the Main Store
Sea salts
As the sea water continued to evaporate, salt minerals known as evaporites began to form and build up on the sea floor. Evaporites form an important part of the Permian Period in Durham and record intervals when the Zechstein Sea dried up. The rise in salinity made the sea floor an increasingly hostile place to live. The animals that lived there were unable to survive.
Background cannonball limestone photograph courtesy of www.northeastwildlife.co.uk
Neogene
Palaeogene
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
PreCambrian
2.6 Ma
23 Ma
66 Ma
145 Ma
199 Ma
251 Ma
299 Ma
359 Ma
416 Ma
443 Ma
488 Ma
542 Ma
4 600 Ma
The National Lottery
East Durham LEADER
HOPE
LAFARGE TARMAC

Figure 12 Interpretation panel explainingmt Permian Geology.

get the aircraft up to shoot down the Zeppelins. The 'mirror' was made from concrete from the local quarries.

- *Marsden Old Quarry* is a site visited as part of one of the Symposium field excursions. It contains two types of Concretionary Limestone, along with some excellent Magnesian Limestone grasslands.
- *The Kingdom of Quarries* leaflet looks at four sites in the south-west of the area, all of which have now become Durham Wildlife Trust sites. The sites are now largely very important Magnesian Limestone grasslands as a result of the quarrying. Some sites are still Primary Magnesian Limestone grasslands, as they were not quarried at all; others, where quarrying has taken place, are Secondary Magnesian Limestone Grasslands.

We also plan to publish a 190-page book called *Built on an Ancient Sea* (Fig. 15, *overleaf*), about the Magnesian Limestone area, showing how the geology links with the historic environment and the ecology. It retails at £12 and will be available from Amazon, or by contacting the Durham GeoHeritage Group by Email at ldunlop@btopenworld.com

Figure 13 The Geotrail leaflets.

A Magnesian Limestone Geotrail. Walk 1
Cliffs, quarries and mills
4-mile walk along the coast from Souter to Marsden Bay & back inland via Cleadon Hill
A Magnesian Limestone Geotrail. Walk 2
Rock in the city
A Magnesian Limestone Geotrail. Walk 3
On top of a tropical reef
A Magnesian Limestone Geotrail. Walk 4
Cliffs, caves and curious rocks
A Magnesian Limestone Geotrail. Walk 5
Coal, clay and quarries
Limestone Landscapes

Figure 14 Panel 1 in situ *in Mowbray Park.*

Community participation

We have also done a great deal of community engagement in geology. At former quarry sites such as Marsden Old Quarry many of the geological features have been uncovered, such as the concretionary limestones. Alongside the geology you can see the orchid-rich Magnesian Limestone grasslands. This helps to get local people with a variety of interests engaged with the sites. Local artist Ant Bryant, as his own initiative, talked to Owen Pugh who owned a quarry just up the road and they gave him any Magnesian Limestone he wanted for carving. Ant did this free of charge and we just had to pay to move the carvings. Figure 16 shows an example of Ant's work — a two-ton rock carving of the lizard of Lizard Lane. He also sculpted a sofa from Magnesian Limestone and an abstract piece. Ant did miniatures of each of these and turned them into treasure hunts round the quarry for local families, who could keep any miniatures of the Magnesian Limestone sculptures they found.

We have also carried out a project called the 'Village Atlas', in which both Paul Williams and Lesley Dunlop have been involved. The original Village Atlas concept came from the Northumberland National Park. Initially they investigated the historic environment of each settlement to see how it developed over time, to find out what is left of the architecture and the archaeology, and to identify what is important and why within the area. This was done as the basis of developing Conservation Areas within the National Park. We thought, as a landscape partnership, that we would like to take this concept further, so we included the geology, the ecology and the hydrology of the settlements, and worked with the local communities and schools to

Figure 15 Cover of Built on an Ancient Sea.

study them. To date we have completed six Village Atlas projects: Wheatley Hill and Thornley; Elwick; Hetton-le-Hole; Ferryhill; Easington; and Cleadon.

The main Village Atlas is a document *c.* 400 pages long. For many of the settlements we have also completed 40-page summaries, which we printed out and distributed in batches of 1,000 to schools and members of the communities. These summaries are now all on our website.

The Village Atlas has been a really successful project, and we now have a bid in to the Lottery Fund to do another 10 of them around the Magnesian Limestone area. We have already had approaches from all the targeted communities wanting to do them. There is a limit to what the records office can cope with in terms of excited local people wanting to find out about the natural and social history of their area.

From the Village Atlas projects there were a number of ways in which people were involved in their local geology. The first and main route was to look at the maps of the settlements and

Figure 16 Lizard sculpture carved on Magnesian Limestone by Owen Pugh in Marsden Old Quarr.

Figure 17 Paul Williams leading a field trip to Easington Raised Beach.

Figure 19 Brian Young leading a Day School at the Tufa exposures on Sunderland Marina.

then visit key sites that illustrated important aspects of their geology. In Easington, Paul Williams took members of the local community out to visit the site of the Easington Raised Beach (Fig. 17), which is now *c*. 50m above sea level and 30,000 years old. As part of the same project he led groups to Warren House Gill to look at erratics from Iceland, part of an Earth Heritage SSSI in that area.

Another way that we have engaged communities is to look at the stones used in the buildings and structures within their settlement. In Elwick, Lesley Dunlop led a tour of rocks from a variety of different sources that had been used in the houses (Fig. 18). Alongside the Village Atlas projects we held a large number of day-schools, looking at the elements of geodiversity outside the six study settlements:

- Brian Young, the former BGS Area Officer, led a tour that looked at a variety of sites around Sunderland, including the tufa in Sunderland harbour (Fig. 19).
- Andy Lane, a local geologist, led a walk around the centre of Sunderland looking at the rocks in the buildings and Parks.
- Paul Williams has led a number of tours at Old Quarrington. Before we built the fossil fishing bay we used to do freelance fossil fishing at the edge of quarries.
- Paul also led a day-school looking at the Cannonball Rocks at Roker (Fig. 20).

Figure 18 Lesley Dunlop explaining the stones used in the buildings of Elwick Village.

All of these events have been well attended, and we have had to repeat them a number of times to cope with demand over a three to four year period. We have also linked events to the historic environment, to biodiversity and to geodiversity, so that the audience can see how these facets of landscape interact.

Training and skills

In terms of the training and skills we have delivered professional development for teachers. We ran a geocaching course to try and enthuse them, and there was also site-specific training, which got them out to a number of the geodiversity, biodiversity and historic environment sites. This was to show how they could use the special nature of this area in their teaching; 98 different teachers have participated.

We have also established geodiversity links to other projects. We restored coastal grasslands from Hawthorn Dene all the way down to Crimdon Dene, which links to geodiversity. The interpretation there also supports geodiversity.

On the escarpment spurs, we did a lot of grassland restoration around Raisby Quarry, up into Coxhoe and Kelloe. Again, this involved a lot of rock work. The staff at Hope Construction at Raisby Quarry were very helpful at involving children and paying for fencing for grazing. We have rare-breed longhorn

Figure 20 Paul Williams leading a field trip to look at the Cannonball Rock on Roker Beach.

cattle on that particular site, which graze the Magnesian Limestone grassland after the wildflowers have flowered and produced seed.

The 'Relics Rising' project restored a number of the historic buildings of the area, including limekilns (which obviously are here because of the limestone), a blacksmith's building at Hetton-le-Hole and the Seaham Lifeboat House. These all used lime pointing, and local geology provided material for the structures.

We taught children about it all through Children's Clubs, running clubs at Cassop Primary School, in Castle Eden Dene National Nature Reserve, and at Seaham. Geology figured in all of them.

Further, we have provided heritage skills training for local people in stone carving and lime pointing.

We advertise this material widely through websites and through Facebook. We have an active community of viewers and contributors; and we have produced newsletters, project updates, publications and books.

I hope that this talk has given you an insight into how we at the Limestone Landscapes Project have been working with the geology of the area and what we have achieved. We hope to achieve more in the future. We would like to get all of the geological SSSIs in the area back into favourable condition. Of these, two or three will be quite a challenge, but we're up for the challenge!

Geoconservation and geodiversity — why it matters: examples from the Permian of the North East

Lesley Dunlop

[OUGS Newcastle Symposium: Pangaea: Life and Times; unfortunately, Lesley Dunlop was unable to write up her lecture as an article for the *OUGS Proceedings*. Therefore what follows is an edited transcription of the recording of the lecture. Transcription was completed by Sally Munnings; editing is by POUGS Editor David M. Jones.]

Absract

Geodiversity underpins and includes biodiversity. It is our rocks, soils, subsoils, landforms, landscape, water and minerals on land and under the sea. It is important that this aspect is valued and promoted with the general population and there are a number of ways that this can be done locally and nationally. The Permian strata of Co. Durham are important resources for local, national and international purposes. Locally the area is used for leisure and educational purposes, with many sites of open access and close to major urban settlements. Nationally and internationally the stratsa are studied for their scientific value to help understand past environments, and by industry — especially the oil industry — to better understand sequences seen in core samples. For these reasons it is important that sites are conserved and maintained. Within the region there are many statutory and non-statutory sites, and recent project work has enabled these to be brought into improved condition. This talk focused on some of the recent conservation work and challenges in the region, and also linked [the issues] to wider UK examples and initiatives, such as the English and Scottish Geodiversity Charters and work done by local geoconservation groups within GeoConservationUK.

Collaboration among the Limestone Landscapes Project [see Tomy Devos, pages 73–80], Sunderland County Council and local geologists has enabled, for example, the quarry at Carley Hill, part of the Fullwell and Carley Hill SSSI, to be cleared and improved, thereby enabling study of a long section of concretionary limestone. Other work on an adjacent 'acoustic mirror' now means there is much for visitors to see. There are many similar projects to improve local appreciation of the geological environment.

The coastal environment and instability of some of the Permian strata does provide challenges for conservation and compromises need to be made between conservation of geologicasl exposures and public access and safety.Recent work at Hartlepool Headland to reinforce the sea wall defences with rock armour has involved covering part of a Local Geological Site. While this is unfortunate, the local authority was able to ensure that an assessment and record was made of the area under threat and to limit the effects as much as possible. Other examples from the region were considered to show partnership and knowledge benfits.

If there is no engagement with geodiversity, then sites, landscapes and aspects of local character can be lost. Projects such as the Village Atlases can make geology more accessable and relevant. Funding of site auditing means geodiversity can contribute more to tourism, lifelong learning and health through walks and site conservation work, as has happened withing such local geodiversity audits.

Thank you for asking me to give this talk.

Geoconservation and geodiversity

I am going to talk generally about the geoconservation and geodiversity issues in England and then focus on the North East Permian. There is some overlap with the subject matter presented by Tony Devos in the previous lecture. It is difficult to follow such an inspiring project as the Limestones Landscapes Project; I just hope they get funding to continue it.

I will start by explaining the word 'geodiversity', as it is one of those words that has crept into our vocabulary over the last 20 years in order to match the term 'biodiversity'. Everybody is comfortable talking about biodiversity, but geodiversity, as a term, is relatively new. It is a good term because basically it includes everything: rocks, minerals, landforms, soils and anything else we can talk about [that affects the landscape]. Geodiversity is what everything else is built upon, so it is the foundation for life, society and people. Also it gives that sense of place, which is what a lot of the Limestones Landscapes Project is about — about the appreciation of where you are.

Those of you from this area are well aware that if you travelled around the places that Tony Devos discusses 30, 40 or 50 years ago, they were entirely different. When I used to go on holiday down to Blackhall Rocks it really wasn't as nice as it is today. For example, there were people carrying coal up from the beach.

The Geodiversity Charter for England was launched in October 2014. You can read about it on the website www.englishgeodiversityforum.org. Scotland also got an excellent charter, which has been in use for about four years, including many spin off activities. You can even join the site's forum. We decided in England that what we needed was something just to promote geodiversity, just a 'handle', snapshots and an explanations of how people could get involved in conserving geodiversity.

The one message, especially true in the north-east of England, but applicable to the country as a whole, is that these charters are 'world class'. For example, if you travel through France, most of the way down to mid-France, you will be in Cretaceous and Jurassic rock for all of that journey. Such homogeneity is not the case if you travel around England — every few miles there is some totally different rock; and this variation is why we decided to work on the Charter. It gives an aim for promoting ways that people can take action and do something about geodiversity.

[Showing a PowerPoint (PP) slide of the West Midlands Dudley limestone caverns] You can see here that the youngster's visiting them don't engage with much. They live on the local estates, on the fringes of everything. So the project is aimed at getting them to do something that engages withthe caverns and what they represent. Because the site is a cavern, and because young vistors can dress up and be 'something different', our work inspired them to become involved in a community project.

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So the Charter's principal aim it to promote ways to share good practice and raise local awareness. It is set out in a way that different groups can appoach it in different ways.

[Referring to a PP slide of the Sunderland North Dock Tufa] This woman is from Estonia. She has come specifically to look at this site, which many people might think is not particularly interesting. However, her group of international visitors came especially to look at this Sunderland site, having learned about it from our work on the Charter. We used the Sunderland North Dock Tufa as an example of how you can work with local developers and industry in order to preserve geodiversity because rock protrudes out of a wall where developers wanted to put a building. They could have easily just destroyed the exposure and built in a nice, normal, square fashion. What they did, however, was to construct the building with a cavity in it so that all of us can go and peer at this bit of tufa 'growing' out of the wall. This is a good example of working together — and if you take nothing else from tis article, please realise that everything about preserving and getting the message out on geodiversity is working with people. If anybody wants me to come and talk about geology, I will.

We owe Natural England for much of the funding to produce the Charter, and also the British Geological Survey who, free of charge, provided the designs.

NE England and the geodiversity partnership

Referring to north-east England, the English geodiversity forum is a partnership; it includes any organisation that wants to be part of it. There are big players and there are the small players. For example, one of the groups in the forum is Natural England. Natural England is responsible for the SSSI network, of which there are *c.* 1,200 in England. SSSIs provide a good link between biodiversity and geodiversity.

Other sites [shown in a PP slide] are part of the geological conservation review, of which there are *c.* 600 that are not SSSIs. Although they are nationally important sites they are not designated as SSSIs because to take them through that process is costly and time consuming. So one of the things we need to work on is to get such sites into SSSI statutory protection — because at the moment they have no protection.

There is also a network of local geological sites, formerly called RIGS. There are *c.* 3,700 such sites, largely looked after by county groups and an organisation called GeoConservationUK, which coordinates the county groups.

[Showing a PP slide of Marsden Quarry] This slide focuses on its flowers rather than its rocks because this quarry is fantastic for its biodiversity. There are rock faces and fabulous sculptures, and what is important is to make links among biodiversity, the geodiversity and any other diversity we wish to bring into it.

Co. Durham, particularly the coastline, has a set of world class sites. The vast majority of it is covered by some designation or other, whether it is a SSSI or other classification.

Tony Devos has already mentioned Carley Hill, and I will now highlight what is happening with conservation at a few other sites. Tony discribed the geodiversity audit for the Limestone Landscapes Project. There is also a Durham geodiversity audit, which encompasses some of the main sites — SSSIs and local geological sites. It is worth reiterating Tony's comment that this is just Co. Durham and that there are other local authorities involved in this coastline conservation — South Tyneside, Sunderland, Hartlepool just to mention a few. Thus our work is collaborative.

For the Limestone Landscapes audit they put out a good descriptive document, worth looking at alongside the BGS document and the sites described in it.

The conservation work at the Carley Hill and Fulwell SSSIs was funded as part of a scheme by Natural England. Unfortunately, most of the funding for the scheme has disappeared and we are having to make applications for new funding, but all is not lost I think. In the Geodiversity Charter Report the geology of Carley Hill and Fulwell is described as being, "famous for its bewildering array of bizarre calcite concretions". As well as being a geodiversity site it is also of historic interest to the local environment. Parts of the site are covered by housing estates, so residents constantly walk around on the footpaths through these SSSIs. Much of the quarried material was for lime burning and was taken out along a wagon track at the Fulwell SSSI.

[Showing a PP slide of the site] The condition of the site was horrendous before it was cleared. The work by the Limestone Landscape Project and the Local Council up to December 2013 removed the trees and made the rock faces safe. This was not easy because the rock strength is not great and there are many small faults in it, as well as folding and undulations along the face. The first bit of clearance left the corner with a whacking crack running down through it. The site has open access, so it was necessary to knock off a bit of the corner so that visitors would not stand underneath it and risk three tons of rock falling on them. Working with the Magnesium Limestone is not easy. To prevent visitors from climbing on top the rock faces, fencing was erected next to the football field. The site looks much better now, as well as being safer.

Hartlepool Headland

Another site I have been involved with recently is at Hartlepool Headland. It is a local geological site on the foreshore on one side of the headland. When the tide is in there is not a lot to see. The local council needed to do urgent repairs on the sea wall, but because it is a local geological site there was the question of how the repairs would affect geological exposures. The rocks are Roker Dolomites, but this site does not have the 'cannon ball' features that you can see at Roker itself.

At the Hartlepool Headland site the dolomite is thinly bedded and there are some oolitic textures. It is cream-coloured, a long section of which can be seen when the tide is out, and which you can walk across to see a good sequence. My examination of it was to see what would be lost from the geological site because the repairs of the sea wall decided by the local council.

The *Hartlepool Star* reported that, "The existing sea wall is in a really bad state of repair. If they don't do anything about it over the next 100 years and if it were to fail, [more than] 500 commercial and residential properties would be at risk of being eroded." The projected cost was *c.* £9M. I would debate the suggestion of "the next 100 years", as I think the coastal erosion will not be gradual but will happen more suddenly due to a big storm or other such event; I do not think you can project over 100 years in that sort of environment.

When I visited the site part of the wall had indeed collapsed, and there was a hole farther back on the promenade that needed urgent repair. Most of the wall had been patched piecemeal

over the last 150 years and had large blocks that were beginning to collapse. The headland itself is also of historic interest. It has [the Norman church of St Hilda], largely built out of the Magnesium Limestone. It has a C20 gun battery, and a sculpture of a hanging monkey linked to the Napoleanonic Wars and local fishermen].

The proposed work to repair the sea wall will likely extend *c.* 12m, and will cover much of the geological exposure in some areas. It is always a difficult decision to make, and geoconservation is always a compromise. But in reality the features that will be covered can still be picked up elsewhere along the seafront here. The bottom line is that, apart from one bit, when the tide is out you can get sufficiently far out to see the features [paying careful attention to the tide times!]

Comparing this site with Roker, at Hartlepool there are fairly thin bedded units with muddy layers within them, some gypsum, and many small cracks on the surfaces of the beds. There are many conjugate joint sets that run out across the foreshore, which are the reason for the erosion. One feature that I was particularly concerned about is the stack, because however I measured it, the edge of the stack is within 12m of the existing wall. So I had to make a recommendation about being careful to preserve the stack.

A number of repair proposals were considered: one minimal and cheap and one with a bit more extensive armour. The geology consultation was considered last — isn't it always?

The conclusion was an option to construct pinning over the wall because the wall is in such a bad state of repair. The rock armour will not be a continuous neat block, but will be spread out. It will give us geologists an opportunity to look at some Scandinavian metamorphics.The repair rock is labelled as being granite, but it is not like any granite I have ever seen — perhaps granite in a stonemason's terminology. The work is ongoing at the time of this lecture.

Marsden Bay

Another area I have been looking at recently is Marsden Bay. Marsden Grotto is in this area and the bit I am interested in extends from the northern part almost down to Souter Lighthouse. This project is another civil engineering project.

The Council is worried about the road that runs up the coast because there are various bits of erosion occurring, particularly in its southern section. I was asked to look at the geological aspects. In a PP slide Lesley pointed out a major fault with various other faults coming off at an angle. The area has been described as one of the most complex stratigraphically and from an engineering point of view.

It is the southern section of the bay that we are interested in, the geology close to the road. Every month my colleagues are making 3D laser scans of the cliffs. They superimpose each month's scans to see if there are any differences. They are looking to see how the cliff is evolving over two years; presently they are about nine months into this project.

The rock strength is weak. A big problem is the dissolution of the anhydrites; there is a lot of disturbance from collapsed breccias and erosion, which, when it gets back to a critical point, will collapse the rock face. In some places there are cemented breccias — different from the collapsed breccias — that occur just where you expect the fault to come along. This analysis is ongoing.

The underlying geology, which on the map looks as if it is all one thing, has a number of other factors coming into play at this southern end. Marsden Quarry is still a working quarry, where the top layers have been stripped, which changes the water flow through some of the faults and cavities. Farther south an old quarry was infilled, but a large hole has developed, also affecting groundwater movement, and the quarry above it will be a factor in some of the erosion. It may even be necessary eventually to re-route the road through the quarry.

Middridge Quarry partnership

Middridge Quarry, which has exposed down to the Carboniferous, has several things of geological interest: some of the oldest plants, and tetrapods. And owing to the ongoing partnerships there is a 3m-wide open access footpath adjacent to it. Anyone travelling between Newton Aycliffe and Shildon can use this footpath, which goes through rocks dating from the Permian to the Carboniferous and passes by the entrance to the quarry. There are steps and access into the quarry and an interpretation board is planned, a good example of what has come out of the partnership.

The footpath was opened in October 2014 and people with pushchairs, people in wheelchairs and the blind can all get along the path safely due to the wide access. An interesting follow-on from this arrangement is that a group of the blind people have expressed interest in other geology walks suitable for blind people's access. (I also work a lot in Berkshire, where you can't see the geology, so I am used to talking about things you cannot see.)

The Elwick Village Atlas

Tony Devos described the Elwick Village Atlas. Elwick is a village near Hartlepool. My involvement was solely just to talk about the geology [showing a PP slide of a 'typical wall in Elwick' and pointing out a bit of the local Magnesium Limestone, a bit of the Whin Sill, and other different materials].

The local people recognised that they were on the Magnesium Limestone, with a large fault running just to the south and providing good views toward Teesside, but initially they did not think they had any of the bedrock in their local buildings as it is covered by superficial material in the local area. So at first they expressed little interest in a project on their local building stones. We showed them that the till coating the local bedrock had in fact brought in most of the locally used building stones; that there were bits of the Whin Sill, igneous rock probably from the Cheviots and other stone types. Materials had been brought down the coast from the Tyne, from the Cheviots, and a lot from the Midland Valley; possibly even some material from the Aberdeen area.

So the hotchpotch of materials in their walls suddenly made more sense. Their local church is built largely out of Magnesium Limestone. We also showed them that bits of Magnesium Limestone in local buildings still looks good, that but the sandstones in the area are really poor, possibly due to pollution creeping up from Teesside. For example, the churchyard gravestone sandstones are horribly eroded. That was something else we could make them appreciate.

North Dock Tufa

A final examle of partnership work with local people is the North Dock Tufa. We hope to get this site designated a SSSI in the near

future. Natural England is working with a group of people to designate, in particular, some local currently depositing tufa sites as part of the geological geoconservation review.

There are two sites in the north-east of this area that are likely to be put forward. One is a site at Dipton, where a small stream has currently depositing tufa, depositing over 89 cascades of the steam — absolutely fabulous. The stream is, however, certainly not depositing calcium-rich water coming from farther up the hill, as these are sandstones (which would be acid). Instead, it is deep water that is bringing that material up.

The reason that North Dock and its tufa are important is that the area is a rare habitat. For example, crayfish like to live in among the tufa and there are several fly species and other invertebrates that only live in this particular type of habitat. It is likely that these two sites will be incorporated into the Geodiversity Charter Report and therefore put forward for SSSI designation.

Newcastle Symposium 2015: Summing up

Dr Tom Argles, OUGS President

(Senior Lecturer in Earth Sciences, The Open University)

[OUGS Newcastle Symposium: Pangaea: Life and Times; original transcription by Norma Rothwell and Maggie Deytrikh from the Symposium recording; edited by Dr Argles and POUGS Editor David M. Jones.]

Before I start the summing up, while I get a chance to do this, I would like to offer a vote of thanks to the organisers of this weekend, which I have thoroughly enjoyed and I am sure that you have too. So thanks to Paul, Karl, John, Olwyn, John, Andrew and Steve.

I have never lived on the Permian in the UK; I have never worked on the Permian at all. So this weekend has been somewhat of a revelation for me, but great fun. There have been a wide variety of speakers plus a field trip today. It has really given me some fantastic insights into both the Period [and] the time, [and into] its paleogeography and also its place in the North East, and particularly latterly, as Lesley [Dunlop] mentions, the landscape and the sense of place that geology brings to a landscape. That is very important as well as just the geology.

But, we will start with the geology, and I must mention that I have a train to catch as well, so this will be relatively brief I think, although I think that we have enough time. Anyone else who has a train to catch, please feel free to leave at any time, and I won't hold it against you, as I may in fact be leaving as well, quite possibly before I've finished!

Paul Williams

On Friday evening Paul Williams was presented to us, fully clothed, which is a bonus! And he gave a lovely introduction to Pangaea and the Permian geology of north-east England; a really good introduction, particularly good as he confessed that he'd spared us the sequence stratigraphy, so that was a real bonus as well.

We learned that the North East was a marine basin, while the rest of Britain he describes by this lovely phrase as 'not so marine'. And because it was a marine basin, you have all those wonderful scenarios that before the Permian there was the Variscan deformation, which set up the particular tectonic configuration of this very restricted basin with a very narrow outlet to the north.

So, first of all in the Permian. You had an arid environment, not a basin environment, a fairly low-lying environment, but an arid desert of those famous yellow sands, the Rotliegend Group. Some of it was so low-lying that it was even below sea level, so it was described by Paul as a 'depressed area'. So, a bit of history there as well. Then there was the Zechstein Sea transgression over this very low sill in the basin at the northern end, with a transgression of the marine waters into that basin and the marl slate being deposited with its fabulous fossil fishes in that very odd euxinic environment, just while the basin filled up. And then as you move on up through the succession, you go up into the Magnesian Limestone, although we're not allowed to call it the Magnesian Limestone anymore, so we have to call it the Zechstein Group. But I'm going to keep calling it the Magnesian Limestone, with all its wonderful different facies, the barrier reefs, the back reef, the shelf, the slope apron, all those sorts of things, with a cross-section right across that Permian basin margin, which has given us such a lovely variety of rocks, particularly to look at today. That concludes Friday evening.

Eddie Dempsey

So we move on to Saturday morning, fortified by breakfast, for most of us, and we move onto the North Pennine Orefield. Eddie told us about his work, which is really cutting-edge, up to the minute stuff, in review, so it's not even published as yet. He explained it as, "It's not what we thought it was"; which, of course, is what all good new work should be.

Throw out the old stuff, they are all talking rubbish, we've got a new theory that we are going to put forward. So we learned that the orefield and the mineralisation was not due to this chimney effect of drawing in the fluids from the Zechstein into the vicinity of the still warm Weardale Granite and then taking those fluids through the granite, picking up all those lovely elements and redepositing them above. This is apparently wrong. It is in fact much more to do with a much more complicated succession of events that he mapped out for us. And he went back to some very detailed work on rhenium-osmium isotopes (Re-Os), which I thought was really nice. I've worked very briefly and tentatively on Re-Os isotopes, with some colleagues in the Open University and it is rather butch chemistry I have to tell you. It involves flame throwing. You have these sealed tubes of *aqua regia*, if you know what that is?

You have to flame the top off so you score around with a scalpel type of thing and then you flame with a flame torch around, and it pings off, usually into your colleagues face, and then you pull this stuff out and commit more unspeakable acts on it. This is Re-Os chemistry, but I didn't do that for long at all, so my opinion of Eddie was raised dramatically as he's obviously a guy who knows what he's doing. So the Re-Os told us that these minerals were deposited and [that] they have [a] similar age to the Whin Sill, about 295Mya and they also have a similar sort of source, a mantle source, which was quite nice; that's from the initial Re-Os ratio.

So a *Mantle* source, something connected to the Whin Sill, both in time and geochemistry, [and] so apparently not much to do with the Weardale Granite at all. And he also pointed out from the structural orientation of these veins that you can see different generations, earlier generations are more aligned to the Variscan N–S compression, and then later veins in the Permian, which are more to do with the N–S transtensional event. So this is when the Permian basin, having been compressed for several hundreds of millennia, then finally got the chance to relax and extend, and then, as Eddie said, it can then start to melt. So that was the story of the Permian basin there.

You will be able to track the progress of this through how many sheets I tear off! *[Tears one sheet off his notepad — Ed.]*

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John Gluyas (1)

So, then, we're onto John Gluyas, part 1, Saturday morning. So he was talking about the petroleum potential of Zechstein carbonates. I had always wondered why the fields got their names. So, all these fields like Morag and Carnoustie, Argyll and Jarvis? And particularly the bird names, as I am a bit of a bird watcher, and I was intrigued why they named so many after birds. And after hearing the story of the Auk field… *[For readers who were not Symposium delegates, the initial idea was that the fields would be named by letters of the alphabet + 'UK'. Thus, 'AUK', 'BUK', 'CUK'... Until it was realised that there would likely be more than five fields! — Ed.]*

So, he was explaining that the Zechstein rocks were not particularly promising as reservoir rocks as in core or in outcrop, they rarely have oil, and the explanation at the end of this talk was that they are perhaps a naturally fracked reservoir. They are naturally fractured, so they are very well interconnected, which is not really the usual form of these things in the North Sea. And so what that means, as far as I understood it, is that when you actually drill into these fields and start producing, you get, in the Zechstein at least, a very rapid peak of oil production, which falls off almost equally rapidly, rather disappointedly rapidly, to almost nothing. But, at the same time, when you've worked that field, you actually have something very close to 98% recovery, which is extraordinary and compares somewhat favourably to the usual 30%, that was prevalent in the seventies and eighties. — although, that has risen up to about 50% today.

So, he also gave a bit of a rundown of other reservoirs as well, most of which he was somewhat disappointed in his work, trying to actually tap the oil out of them. But he talked about the Rotliegen sands again, so beautiful reservoirs, but as far as I can gather generally containing far more water than they contained oil. So you tend to have a peak of oil, then it very rapidly drops off and then actually gives off mainly water. And then the Devonian reservoirs below that, which are very variable and patchy, some very good, some not so good. And then, at the end of his talk, he added a kind of footnote to his talk overall, which was considering the oil price recently — as there's been a real drop in the oil price recently — over the last year and a half or so, and that has very serious implications, at least in the short term for North Sea Oil; and could it possibly even mean the end of North Sea Oil, not because there's no oil left.

It's quite clear from his other talk [on Saturday afternoon] that there's plenty of oil left, but it is not economic and it will become increasingly difficult to get out of the ground.

Paul Goodridge

So, we moved on, still Saturday morning, to Paul Goodridge, with a change of pace here, looking at the End-Permian Mass Extinction. This was a more philosophical talk — I quite enjoyed this. So, it was looking at the period in the Permian, when "the Earth almost died", as he said. He started off, spending quite some time, deploring the excesses of 'info-docu-entertainment' channels, which he was clearly not very happy with at all. I don't think that he actually gave the names of the presenters. I am not going to even try and speculate, but I am sure that you have your ideas. One of his other points, of course, was that extinctions may be sensationalised and made catastrophic, but he was saying that extinction is actually normal and he showed a number of graphics, which showed that extinction is normal, goes on all the time, sometimes it goes along at a higher rate and that's when we need to worry. He also made the point that it is one of the things that we need to worry about now. But it is very difficult to measure that rate. But, even regarding the fact that extinction is normal, the Permian clearly wasn't a very good time to be around, for pretty much any species at all for all sorts of reasons.

And then, for the rest of the talk, he went through a whole list of possible reasons, staring from the expanding earth hypothesis, which he didn't spend long on. Gamma-ray bursts from a neutron star, which was new to me. I haven't heard that explanation for the End Permian at all. Asteroid impactor, which is a very common potential culprit. But, also that interesting theory of the antipodal disruption that you get from an impactor, so it's not exactly just where the impactor hits, and the effects that it has from that, but it's also what happens on the other side of the planetary body, the structural disruption and possibly all sorts of geochemical effects that are initiated on the opposite side from where the impactor hits. And so, it looks as if palaeogeographers are going to have endless fun, not just picking spots where impactors have actually impacted, but also [finding] what's on the opposite side of the planet, where they have caused all sorts of mayhem as well. So you get double your money for that kind of research! And that led on in turn to a consideration of possibly the Siberian Traps, which may or may not have been initiated by one of these impactors, from Antarctica perhaps, but possibly represent up to two million years, maybe as little as 600,000 years of basaltic eruption, still quite a lot of eruption, and then preceding that, by a few million years [when] there was another series of traps, in China, the Emeishan Traps, which, again, were a protracted period of basaltic eruption. And then, to cap it all, you don't just erupt a whole load of basaltic magma, ash and so on into the atmosphere, but you also ignite Siberian coal deposits at the same time, and just have a big bonfire as well! So, clearly, the End Permian was not a great time to be around. And then he also mentioned, just in case that wasn't enough, oceanic anoxia, potential methane hydrate release, and he mentioned 'hazy green skies', which I thought was rather nice; so, essentially, the End Permian was a bit exotic, and a pretty horrible time to be around. Most species decided that they would stop being around and they gave up and died.

John Gluyas (2)

So, then we move onto John Gluyas, part 2, on Saturday afternoon, looking at the 'Reservoir quality evolution in [the] Permian', looking at the Rotliegen Sandstones of the North Sea. He started off with a nice image of an alluvial fan, in Leh, in Zanskar, which is in the Himalayas, where I have worked for quite a lot of time on structural metamorphic stuff. So that took me back and it was nice to have that different perspective. And then a few more slides of the scale of these sedimentary systems, even in the modern world, but also looking back in time, with modern analogues in the Namib Desert and [in] the Sahara, with these vast sand seas, as well as these ephemeral river deposits and wadis and these massive alluvial fans. We try to get into our heads a sense of the scale of these packages of sediment, which were then actually forming in the Permian basin, the Zechstein basin.

So, looking at things that are at least equivalent or even larger than some of those oil and gas fields out in the North Sea, [John asked the question] "So, why are those fields so small?" So, he explained that actually what you are looking at is that those fields

are segmented; they might be broken up by later faulting, they might be domed up by salt domes, for example. But equally, they might have smaller scale things like faults and granulation seams cutting through them, and each of those is potentially segmenting that large sedimentary package into much smaller pieces, which can then act as individual segmented reservoirs. And he had a nice exposition of the role of baryte, as a cement, which is a bit strange, considering that they pump it down the hole to get the oil out in the first place. So that's one way he explained of clogging up a hole, pump the baryte down, cement it all off, that's it, then you're not going to get anything out of it. Then he looked closely at different cements in these Rotliegen Sandstones: illite clay cements, carbonate cements, maybe baryte cements and dolomite cements. He'd looked into the source of the illite recently. The pore water for those Rotliegen Sandstones is Jurassic rainwater, but he was puzzled by where the aluminium for that clay mineral came from? And his thesis at the moment is that, along with the iron oxide, if you think of a desert varnish type environment, there's bauxite dust, there's actually aluminium dust around in the very deep tropical weathering that you would have at that time, in that arid environment. So, you have bauxite dust, which is, of course, mostly aluminium oxide, and that coats some of the grains as well as the iron oxide. So, that could provide an *in situ* source for the aluminium, rather than invoking all sorts of weird fluids as something [that] would have been able to bring the aluminium in, from farther away.

And just as a last aside from John's talks, which I really enjoyed actually, I am looking forward very much to his forthcoming paper 'Pyrites of Penzance'. I had to make that joke again, too good to miss!

Neil Rowley

So, Saturday afternoon, with Neil Rowley and we had a slight change of scene again — and we were looking at mining in the Zechstein evaporates at Boulby. Now, I've never been down Boulby, I'd love to go. It seems to be a shame as they're thinking of scaling down those visits, which is a real shame. Amazing engineering that's required to mine these potash salts, from not just under the ground, but seven miles out into the North Sea; and presumably 'fingering' out all these different roadways under the North Sea, and keeping those markets supplied. But, also interesting, apart from the engineering, was the recent price rise, which saved Boulby in the late 2000s [c. 2006–7]. So, [Neil then] explained that the company was spending money "like a drunken sailor", which was rather nice for this part of the world. So, that fantastic description of, "We need a new shaft"; "Let's just do it"; "It doesn't matter how much it costs, but how are we going to do it?"; "We can't close the mine down for more than about three weeks"; "Can you do it in that time?"; "Oh, probably, yes, we'll draw some plans up and see what we can do?" But then, I thought that was absolutely extraordinary: you just cut it off at the base. This is like primary school engineering. You just cut it off at the base, shift it over there, and then we'll have the new one and we'll just put that in; 'Bobs your uncle!' — and it worked; extraordinary!

A fantastic story. I loved that talk, I could have gone on about that talk forever. The last thing that I learnt from [Neil's talk] that I wanted to just remind you of, was that I now know why the North Sea is so salty? It's because of all the amount of salt pumped out of Boulby!

Karl Egeland-Eriksen

So, finally on Saturday, we came to Karl [and] 'The history of Permian geological investigation in north-east England'. There was an early slide of an old portrait of an old geological gentleman, but he didn't have a beard! This took me back to writing OU courses over a number of years, where each first time, we'd sit down for the first time with the module team and think about the content. First thing; how can we introduce the subject? And so often, we would look back at the old books and we have a whole succession of photographs of ancient geological gentlemen with beards. They all had to have beards. So, it's actually quite a nice change to see a whole succession of geological gentlemen, very few of whom had beards! Some of them had quite impressive sideboards but not beards. So, that was a nice change.

So, Karl mapped out for us beautifully this voyage of discovery of these various geological gentleman, or not even geological, as most of them actually were medical early on, which is slightly alarming. Mapping this journey of the Magnesian Limestone, from magnesia alba through to, what was described as 'calcareous manures' — an interesting thought, although we did see some peloidal mudstones today [on the field trip], so I guess they are, kind of, 'calcareous manures' — through to 'hot lime', which sounds like some kind of pop group.

And then we went through all these different characters. I am not going to name then all [but they included] Smithson, Tenant, and James Sowerby, via some real giants' names — Sedgewick, Buckland, Murchison, the giants of geology, [and] Louis Agassiz. And then through some local characters, such as King, Howse and Kirkby, who had these slightly tricky relationships at times in the local community, fighting to be curator of the local museum. Interesting thought. And then right up to Dennis Smith, who was described as 'Mr Permian'. You've heard about Mr Smith, but that will have to wait for another time.

So, thank you to Karl for that, it was a really nice change of pace at the end of the day.

We then had an excellent dinner. That was very good, followed by the ceilidh and I think that the less said about that the better. I am sure that you all enjoyed yourselves. And then, we came on to today. We had the Sunday field trips. I remember this morning, lying in bed for a few minutes, thinking 'Is that the shower or is it rain?' As it turned out, it really worked out fairly well. I think that we only got rained on very slightly, no more than a refreshing sprinkle, so that worked fine. I had a great time. You can't really ask for much more than spending a day on the beach in the sunshine and ending up in a pub, a very well-designed trip, in the true traditions of geological fieldtrips! "Did nobody else go for a pint?"

Tony Devos

Then finally, we ended up back here and we listened to a lovely couple of talks with a slightly different emphasis this afternoon. Tony, on the limestones landscapes project, national character areas, which I've read quite a bit about actually, while trawling through the internet for ridiculous facts to put into OU courses to wake the students up. So, a really nice rundown of what they're doing — and they're obviously doing a huge amount of work. So, yes, they got a fair amount of money from the lottery and a lot of help from partners, but they are doing a huge amount.

They've done a geological audit with the BGS, conserving and restoring the quarries. I did like the description of one of the quarries, prior to their work, as a 'Bring your own machete quarry'! Access to live quarries as well, both for adults and school children. 'Fossil fishing', that was a brilliant idea, absolute genius. I've been to Quarrington and done the Quarrington experience and done my own fossil fishing experience, but having it in a primary school is just a genius idea I think. And some of the engagement figures that he was coming up with; nearly 5,000 primary pupils engaged in this project from 200 or so schools. That's just amazing. And the trails and tribulations pamphlets. The book that's coming out, which I might just do a quick plug for again, in October, village atlases, more field trips, an amazing amount of work that's been going on, really inspiring. And good to hear that he's still up for further challenges.

Lesley Dunlop

And, finally, we come to Lesley Dunlop, at the end of the day: Geoconservation and Geodiversity, why it matters.

I have a couple of quotes here: "Geoconservation is always a compromise". I did like that. The feeling that you are constantly, not quite treading on eggshells, but constantly jockeying position, constantly manoeuvring, with both partners and the opposition — [with] everybody involved, I suppose the name you would call them nowadays would be 'stakeholders'. So, geoconservation, quite a tricky subject. We tend to think of maybe anyone who's involved with any kind of conservation just wants *their* bit. We want to make it the way we want it, but it's not as easy as that; as you've always got lots of other people involved. And her idea is that geodiversity is the foundation and that not just geology as the foundation of the landscape in the physical sense, but also in a historical and cultural sense, and it gives it that sense of place. And I don't know if this kind of thing is happening in any other country? These character areas, if you like — because it's certainly something that I think is almost unique to the UK, certainly on that smaller scale, that you get such a difference as you drive or go by train from district to district, because of the changing geology and the changing biodiversity that goes with that. It's a lovely country to live in and it's wonderful to come to a place like the North East, which is, I think unique in Europe and has some of the best — Paul [Williams] mentioned this a couple of times — some of the best geology in Europe, some of it absolutely world-beating. I just thought that I'd throw that in again.

So, Lesley is talking about saving tufa sculptures, such a variety of things, making quarries safe and making quarries visible, which is always nice. And the bewildering array of calcite concretions in some of those quarries, but she's [also] dealing with things like rock armour coastal defences, laser scanning of cliffs, which we've done a bit with laser scanning of inland sites for virtual field trips. It's quite fruitful work at times. And then looking again, back to the villages and the building stones in the villages.

So, I think a wonderful span and scope of different talks, all through the weekend. I'll leave you with the last thing I learned from Lesley's talk which was — it kind of overturned a myth that I'd had in my mind for pretty much forever from OU studies — that "sandstone is not always more durable than limestone", and I think that it's quite a nice note to end on for our weekend with the Magnesian Limestone.

So thank you very much.

Mantle in the Mountains: a geological excursion to the Betic Cordillera in Málaga and Granada Provinces, Andalucía, Spain

OUGS President's Trip 2015: Leader Dr Tom Argles, Organiser Jan Ashton-Jones

Authors: Jane Browning, Sam Capstick, Caroline Deans, Linda Fowler (and editor), Mellissa Freeman, Chris Hodgson, Terri Newton, Michael Perkins, Bernard Skillerne de Bristow, Paul Speak, Oliver Strimpel and Stuart Swales

Other participants: Pete Hodgkinson, David M. Jones, John Lamont, Margaret Poole, Muriel Rogers and Paul Taylor

Latitude and longitude of locations are indicated in degrees decimal; images are by the individual authors except where otherwise indicated.

Introduction

The OUGS President traditionally leads a field trip in his or her second year in the position and Tom suggested that revisiting his PhD area in southern Spain would be an interesting focus for his trip. Jan Ashton-Jones, aided by Linda Fowler, offered to organise the event and loaned their holiday cottage between Antequera and Granada to Tom and his family for a reccy in the preceding October.

The Betic Cordillera is a geological domain distinct from the rest of Iberia and lacks the older basement terranes and Hercynian deformation found elsewhere in Spain. It lies at the western end of the Tertiary Alpine-Himalayan mountain belt and is dominated by folding and thrusting resulting from compressional tectonic processes. Locations visited were mainly in the Internal Zone between Ronda and the coast, in the External Thrust Belt near Antequera, and in the Internal Zone south of Granada. Much of the trip was based around the large peridotite bodies exposed in the western Betic Mountains. These have been Rh-Os dated at 1.36Ga, the date when the material moved from mantle to continental crust. This article is an account of the trip by those who took part and, while it describes the locations we visited, does not attempt to explain the overall geology in any detail.

Day 1 — Wednesday 29 April

Overview from Málaga to Ronda

Linda Fowler

Our group of 20 met up at Málaga Airport during the morning of Wednesday April 29, picked up rental cars and set off towards Ronda, the first base, where we stayed at a traditionally Spanish hotel, centrally located between the *Puente Nueva* and the historic bull ring.

Our route from the airport initially took us south-west above the coast and then inland from San Pedro de Alcántara to Ronda. We made an incidental first stop for coffee and *tapas* at the Arroyo de Miel service area on the AP-7 toll road and took this opportunity to 'get our eye in' on the Palaeozoic marble exposed in the cutting behind the restaurant before heading up the 1970s 'tourist' road (A-396) from the coast to Ronda. This road was upgraded from a 'C' road to take coach tour traffic, and is unusual in that it does not pass through any towns or villages.

At a cutting near Km 34 [36.558176, –5.052443] we stopped for a view over the coast and had our first lesson in spotting peridotite locations — they are covered in pine trees, which seem to prefer this substrate. Rock fragments at the roadside included carbonates from nearby quarries, the local peridotite, metagranite (which has black specks of chromite and spinel on joint surfaces) from below the peridotite sheet, and apparently waterworn pebbles of migmatitic breccia (aka lithoclastic gneiss), some of which contained post-kinematic garnets (Fig. 1.1). We found various examples of this stretched, flattened, folded and refolded material containing blobs of quartz and lithic clasts (Fig. 1.2, *overleaf*).

At a second stop on this road, just past the Pujerra turn at Km 24.5 [36.614832, –5.070215], we were able to see the remarkably clear surface vegetation expression of the junction between the pine-tree-covered peridotite and the bare hillside of *Dorsale Limestone* (Fig. 1.3, *overleaf*).

Figure 1.1 Post-kinematic garnets have grown across the fabric of the lithoclastic gneiss in this hand specimen.

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Figure 1.2 Folding seen in a hand specimen of lithoclastic gneiss.

Figure 1.3 View NW from Km 24.5 to the steep, faulted junction between pine-clad peridotite and poorly vegetated limestone.

Day 2 — Thursday 30 April

Sierra Bermeja peridotite and underlying gneiss

Linda Fowler

On the following morning we headed back down to Estepona on the coast and then took the MA-557 towards the *Sierra Bermeja* peridotite massif, where we stopped initially in a car park at *Puerto de Peñas Blancas* before heading off for the main locations along a forestry track. *Los Reales de Sierra Bermeja* is a *Paraje Natural* (Protected Natural Site) important for being one of the largest outcrops of peridotite in the area. This rock gives the mountains their characteristic colour and their name: *Bermeja* translates as 'ginger or russet coloured', which is certainly true of peridotite hills.

Puerto de Peñas Blancas [36.480193, –5.200316]: In the back wall of the parking area we found a leucocratic dyke, almost horizontal in aspect (Fig. 2.1). This quartz- and plagioclase-rich dyke has an annealed fabric with brittle fractures, which are a response to post-cooling stress and contains diopside and blue-green chromite (Fig. 2.2). It has probably been injected from below into the country rock, which at this point is plagioclase peridotite indicating shallow mantle origins. Farther up the hill the country rock is granular, spinel peridotite with garnets and tectonic foliation; although it initially appears odd that the higher-pressure rocks are topographically higher, they represent different time steps in the story. The peridotite sheet was thrust over material that was originally a breccia, and heated the latter to the point where shallow partial melting took place to produce a matrix of low-pressure granitic melt.

From here we drove down the hill and then some 2–3km along a forestry track [36.498060, –5.198620 to 36.513400, –5.207472], which contoured around the hillside to the north of *Pico de los Reales*, to explore the distribution of mafic layers within the peridotite (Figs 2.3, 2.4, 2.5, *opposite*). In some mafic layers the garnets are small swells in the thin layers of 'marginal mylonites', which also include a lineation of aligned, elongate orthopyroxene crystals (Fig. 2.6, *opposite*).

Figure 2.1 The leucocratic dyke at Puerto de Peñas Blanca is almost flat lying.

Figure 2.2 Close up of leucocratic rock in dyke at Puerto de Peñas Blancas.

Figure 2.3 The forestry track north of Reales (a rather bumpy track made focusing difficult). The 'spinel peridotite with foliation' passes into a 'garnet peridotite' zone where the garnet occurs in thin mafic layers. The mafic layers form by partial melting of peridotite in the mantle where it is in contact with the overlying crust; the resulting rock is then deformed and stretched.

Figure 2.4 A trackside exposure shows that the mafic and ultramafic layers weather differentially.

Figure 2.5 Searching for good examples of mafic layers in the peridotite.

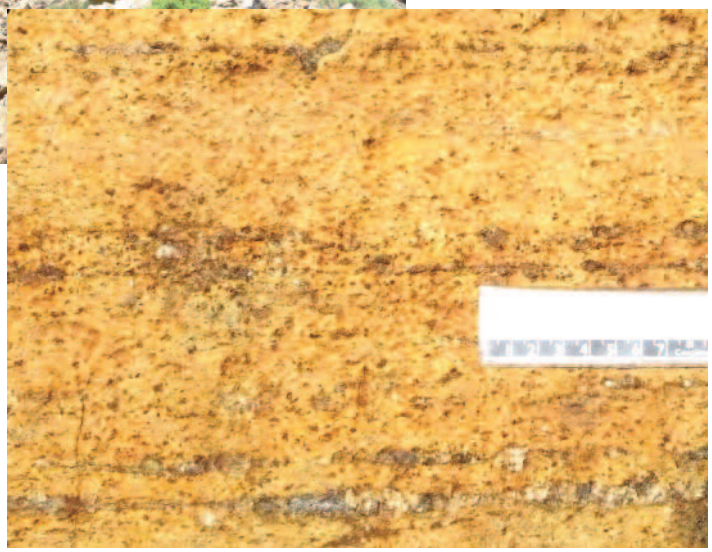


Figure 2.6 Weathered peridotite with mafic layers and garnets. (It was along this stretch that we saw our one and only small, brown, Mediterranean Scorpion Buthus occitanus and realised the sense in Tom's advice to kick stones over before picking them up! These scorpions are not as dangerous as their North African cousins but can still give a nasty sting.)

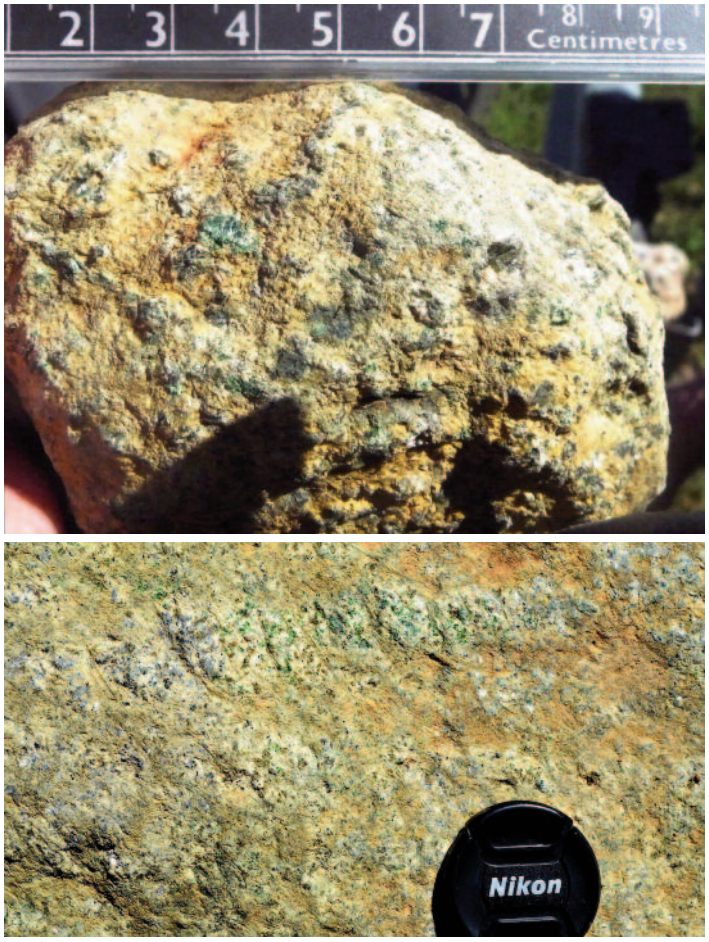
We drove back to the *Puerto de Peñas Blancas* and up the winding track to the *refugio* on the mountain of *Reales* (1,452m) itself, where we parked and walked to a *mirador* [36.476681, –5.201038] that gave us splendid views of the Betic Cordillera curving round, through the Straits of Gibraltar, to the Rif Mountains of Morocco and enclosing the extensional basin of the Alborán Sea (Fig. 2.7, *overleaf*).

The final stop was at a location in the stream bed of the *Arroyo de la Cala* [36.478816, –5.180897], 1.9km east of *Reales* and some 750m lower, to see the lower contact between the peridotite body with the underlying crustal rocks, the 'lithoclastic gneiss' (Fig. 2.8, *overleaf*): we knew we were not on peridotite as there were no pine trees! The bedrock here was also described by Tom as migmatitic breccia, and is like the loose cobbles seen at the first stop on the previous day. Boulders, which must have come from higher upstream, contained chromite diopside in single crystals and in layers (Fig. 2.9, *overleaf*).

Figure 2.7 Clear weather at the mirador at Reales enabled us to see the splendid views south and south west to Gibraltar and Jebl Musa: the Pillars of Hercules, and even round to the Rif Mountains of North Africa.

Figure 2.8 Arroyo de la Cala: a stream section through the unit below the base of the peridotite sheet.

Figure 2.9 (a), (b) Peridotite with layering and chrome diopside crystals from Arroyo de la Cala. ((b) SS).



Day 3 — Friday 1 May

Cueva de la Pileta

Jane Browning

We set off in good time to be at the *Cueva de La Pileta* [36.691345, –5.268587] promptly, as there are no set times for tours, so the guide waits until there is a sufficiently large group to begin. *Pileta* can mean bowl, sink or trough, a bit of a misnomer as there was quite a climb up a rocky path from the car park to the entrance of the cave, on the side of the Guadiaro Valley some 670m above sea level. The caves are a nationally protected site. They are still owned by the descendants of the family who found the caves in 1905 and are totally uncommercialised. Lighting was purely by torchlight, but there were handrails to help negotiate the more tricky parts of the route. Note-taking was impossible in those conditions and the guide asked that no photos be taken.

Figure 3.1 The painting known as the Yegua preñada 'pregnant *mare' is a symbol of the Serrania de Ronda. This photo was taken of the information board at the entrance (LF).*

The limestone caves and the associated stalactites and stalagmites were impressive and I am afraid I could not do justice when attempting to describe the tremendous variety of formations that we saw. There was one particular wall that was akin to huge organ pipes extending way up to the heights and, just as it appeared that we had surely reached the end, another cavern would appear. We were told that there were many other caves, on different levels, in addition to those we visited. There are two prehistoric 'schools of art' in the caves. The first dates from Cro-Magnon man, approximately 25,000 years ago in the Upper Palaeolithic Period, with paintings of horses, goats and fish (Figs 3.1 and 3.2). The more common charcoal scratchings are attributed to the Mesolithic Levantine School and contain a number of zigzags and stick men; many of these are of archers hunting their prey.

Figure 3.2 Pileta's most famous drawing: a large fish (thought to be a halibut), about 1.5m in length, with what appears to be the outline of a seal inside it, is at the end of the longest gallery in the deepest part of the cave, the 'Fish Chamber'. This photo was taken of the information board at the entrance (LF).

Low grade Alpujárride cover of peridotites, Internal Subbetic

Sam Capstick

We then headed through the valley in Subbetic formations and climbed over a ridge passing the contact of the Mesozoic Dorsale Limestone. Stopping near Benalauría [36.594572, –5.270558] we saw beautiful chevron folds (Fig. 3.3, *overleaf*) and fault breccia in pelitic carbonaceous Maláguide rocks: these are Silurian or Carboniferous in age. The pelitic rocks were interbedded with coarse sandstones rich in mica and quartz clasts (up to 10mm); these were more resistant to folding and, instead of forming chevrons they faulted and fractured (Fig. 3.4 *overleaf*), with fault breccias where striking hematite and calcite crystals had also formed.

After a picnic lunch we drove down the road towards Jubrique to a contact between the Maláguide and Alpujárride units with schists and phyllites [36.567001, –5.228095]. The jump from very low grade to significantly higher-grade metamorphism proves that it is an extensional contact and part of the section has been lost. The Alpujárride unit is rich in deformed quartz veins, which you would expect to have been intruded post-kinematically. This is not the case as they directly link to the metamorphism, during the pulse of heat caused by crustal thinning that placed the body of peridotite closer to the crustal rocks. The minerals that surround or replace the quartz give an insight into the metamorphic conditions acting as a field barometer of temperature and pressure. Feldspar and mica were found but, more importantly, andalusite formed, which shows that the elements needed to form aluminium and silica have diffused out of the local rock, enabling these minerals to crystallise on the outer edges of the quartz veins (Fig. 3.5, *page 95*). In addition, this diffusion picks up graphite from the local rock, which gives the andalusite its pale pinkish-red colour.

On the return journey we stopped at Atajate *mirador* [36.642465, –5.237236]: this provides a viewpoint of the three main units: peridotite, Maláguide and the Dorsale Limestone. The road-cutting exposes red and white striped Cretaceous marls where a block of this has been down faulted into the older Dorsale Limestone. The red beds are muddier and take up the strain, while the white is more lime-rich and does not warp in the same way (Fig. 3.6, *page 95*).

Day 4 — Saturday 2 May

Miocene (Tortonian) clastic sediments of the Ronda Basin in the Cerro Tajo Gorge

Terri Newton

The majority of the group met up outside our hotel and set off on foot to *El Tajo* gorge, to view some fantastic exposures of Miocene (Tortonian) clastic sediments of the Ronda Basin.

Figure 3.3 (a, above) and (b, right) Clear chevron folds in the Maláguide rocks at Benalauria (SC).

Figure 3.4 (below) Brittle deformation in the Maláguide rocks at Benalauria (LF).

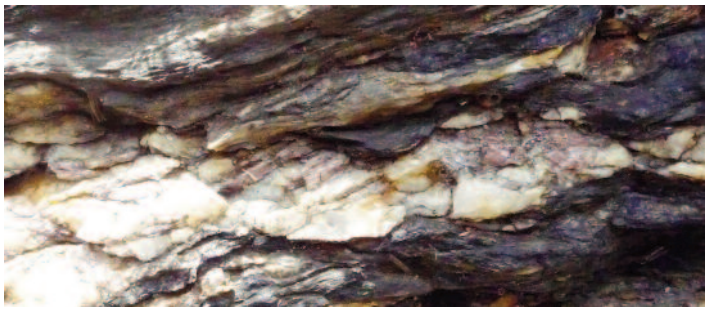


Figure 3.5 (above) Pink andalusite in situ *on the edge of a boudinaged quartz vein, the boudins are* c. *50mm long (LF).*
Figure 3.6 (right) Tectonic structures in Cretaceous sediments at the Mirador de Atajate (LF).

The Ronda Basin forms one of several late Miocene embayments bordering the southern edge of the Guadalquivir Basin, which at this time was under Atlantic cool-water influence. The Upper Miocene clastic sediments of the Ronda Basin now exposed in the Cerro Tajo Gorge are divided into three depositional sequences within a ramp system:

- Sequence 1: Tortonian conglomerates and marls
- Sequence 2: Late Tortonian to Early Messinian carbonates (inner ramp) and siliciclastics (middle and outer ramp)
- Sequence 3: Messinian carbonates (inner ramp) and siliciclastics (middle and outer ramp) (Gibbons and Morena 2002).

El Tajo gorge is steep, narrow (68m at its widest) and deep (up to 120m), and was incised by the constant erosion of the Guadalevin River, which is fed by mountain streams and snow-melt from high in the *Sierra de Las Nieves*. The gorge divides the city of Ronda into two sections: the old Moorish area, *La Ciudad* ('the city') and the new town, *El Mercadillo* ('the little market'). In 1793, after 40 years in construction, Ronda's 'new bridge' the *Puente Nuevo* was completed, providing a connection between the old and new towns.

The trail down El Tajo begins on the north side of the *Puente Nuevo*; the main path takes a zigzag course and is made up of a series of wide stone steps that eventually give way to a regular dirt track. As we hiked down the track the views of the gorge and *Puente Nuevo* in the distance became ever more spectacular (Fig. 4.1) and we observed soft-sediment structures formed by dewatering and erosion structures (e.g. channels) in the sides of the cliff face. We also searched for marine fossils, as Tom said they are abundant in the Miocene sediments of the Ronda Basin, although all we managed to find were some scarce trace fossils in the path down the gorge (Fig. 4.2) and some isolated fragments of bivalve body fossils in a man-made wall at the end of the trail: thus the bivalve fossils were likely not *in situ* but brought in from elsewhere. At the bottom of the gorge, to our delight and surprise, we found a café where we rested for a short while before making the somewhat harder hike back up.

Figure 4.1 Tortonian sediments exposed in El Tajo gorge by Ronda's Puente Nueva (SS).

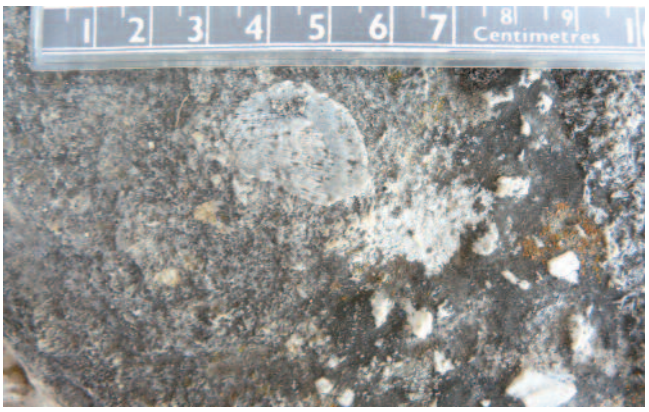


Figure 4.2 (above) Trace fossil in Tortonian sediments by the path down El Tajo gorge (SS); and (below) a bivalve fossil (DMJ).

The Ronda Basin and Mesozoic carbonate scenery around Montejaque.

Mellissa Freeman

After lunch we drove towards Montejaque, stopping on the way to view the dam and landscape [36.753980, –5.234806]. Jurassic limestone blocks are surrounded by Cretaceous marls with flysch covering both. The limestone has been strongly deformed, with near vertical bedding in places; and apparently there are abundant fossils.

From here we drove up a track just before Montejaque village, and parked [36.745282, –5.253180]. Our first stop was to look at rocks of the External Zone of the Subbetics. These sedimentary rocks were deposited near the margin of the late-stage, extensional Ronda rift basin. Rifting occurred during the Jurassic in this region breaking up some of the carbonate platforms and margins forming horst and graben, half-graben and some slightly deeper troughs as well. The platforms are dominated by Jurassic limestone and the troughs contain more hemiplegic Tortonian sediments similar to the red and white interbedded marls and limestones we saw at the *Mirador de Atajate* road-cutting the previous day (Fig. 4.3). These poorly sorted Tortonian sediments represent fan delta deposits / siliciclastic turbidites and lie unconformably on the internal and external zones (Fig. 4.4).

Underfoot at this location is the flysch, a mélange of sediments, which are the product of the mountain belts that were forming in the vicinity during the early Miocene; the flysch sits, stratigraphically, between the Subbetic and the Ronda Basin. The mélange is mostly marine in origin with Jurassic carbonates, possibly from the Subbetics or Dorsale Units, occasional Maláguide rocks, deep water clays (brown or tan coloured) and fine grained erodible flysch muds. Sandstones in the earliest, Neo-Numidian flysch have frosted sand grains thought to be of desert origin, possibly derived from the Sahara / Neo-Numidian deserts. These units are easily identifiable because of the change of the landscape from rocky outcrops to a rolling pastureland topography of ploughed fields and olive groves.

Near here we viewed a limestone anticline and knoll. Here Cretaceous marls sit on top of limestones forming a thin skin. The knoll is possibly an olistostrom block (Fig. 4.5).

Our final stop, as we returned along the track, was to view the rocks in the small *Mirador del Pantano* quarry [36.745276. –5.253159]. Here the limestone blocks were strongly deformed, mostly limestone breccia boulders that were not *in situ* (Fig. 4.6, *opposite*). Within the limestone we also saw chert layers (Fig. 4.7, *opposite*). This suggests deeper water, which may have been caused by a sudden tectonic shift or trough subsidence; this would have pushed the local area below the Carbonate Compensation Depth (CCD) so that only siliceous sediments were deposited. In this case, although we saw carbonates above and below the chert, indicating that something had happened to bring the area back above the CCD. There was a lot of supposition during our evening 'sum-up' with Tom: one suggestion was that this could be explained by a radiolarian bloom changing the sediment type being delivered to the ocean floor to silica, overwhelming the carbonate deposition for a short period of time.

The return journey gave us a good view of the dam at Montejaque (Fig. 4.8, *opposite*).

Figure 4.3 Red and white interbedded marls:oxidised division in Montejaque carbonates (DMJ).

Figure 4.4 The change in lithology between limestone above and marl below is marked by a change in slope and a change in vegetation at the first stop (DMJ).

Figure 4.5 View of limestone anticline and knoll.

Figure 4.6 Calcite crystals found in the limestone at the Mirador del Pantano quarry (DMJ).

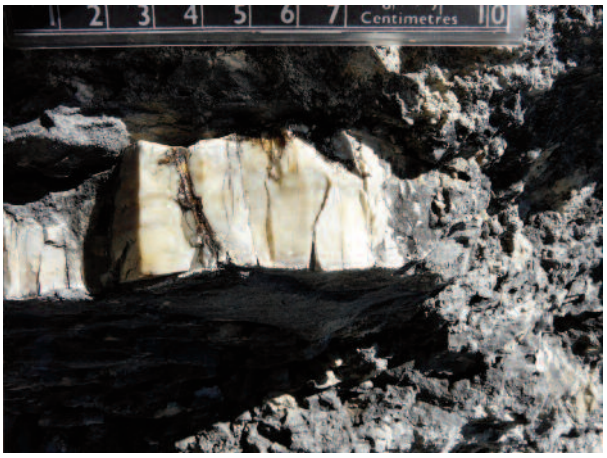


Figure 4.7 (above) Looking at the chert layers at the Mirador del Pantano quarry (MF); and (left) a detail of the chert layering (DMJ).

Figure 4.8 The dam at Montejaque is built across the gap between two blocks of limestone (LF).

Day 5 — Sunday 3 May

The peridotite/limestone contact, the gneiss/peridotite contact, gneisses near Pujerra, peridotite and kinzigites on the track towards Peñas Blancas

Oliver Strimpel

Retracing our first day's route from Málaga to Ronda, we drove south on the A-397 to investigate another exposed boundary of the Sierra Bermeja peridotite massif, this time with Mesozoic limestones [36.626028, –5.077827]. The road-cut presented the best exposure, both of the contact itself, and of the progression of increasing impact of the peridotite emplacement on the limestone country rock (Fig. 5.1). Approaching the contact, over a scale of a few metres, undisturbed limestone gave way to a sheared, but not a recrystallised section, then to a partially mylonitised strip, and finally, within a few tens of centimetres from the contact, to an intensely mylonitised, sheared, and stretched fabric (Fig. 5.2).

Darker layers from compositional variations in the original bedding helped to highlight deformation. The peridotite, heavily serpentinised near the contact, showed only brittle faulting, implying that the whole crustal section had already cooled when it was emplaced over the limestone, and suggesting a fairly shallow level of emplacement.

Figure 5.1 Investigating the contact between peridotite (weathered brown foreground rocks) and Mesozoic limestones (white-grey) along the A-397 South of Ronda.

Figure 5.2 Intensely mylonitized limestones adjacent to the peridotite contact.

We speculated as to the sense of the fault, but the lack of larger-scale shear sense indicators made it hard to corroborate the contact as the steeply dipping thrust fault shown on the IGME geological map. Small-scale indicators probably only reflected post-emplacement movements, perhaps associated with exhumation. Since the rocks had already cooled, this may be a late stage fault. But its age is difficult to determine because no minerals in either the peridotite or the carbonates are readily amendable to dating.

To reach our second contact of the day, we turned west off the A-397 towards Pujerra, where we found a contact between the peridotite and the structurally overlying Alpujárride gneiss (unlike the gneisses we saw earlier near Estepona, which were underneath the peridotite) [36.599652, –5.116209]. The extent of the peridotite was clearly delineated by the tree cover: almost exclusively pine on peridotite; and chestnut, cork, and other vegetation on the surrounding gneisses. The peridotite was not as heavily serpentinised at the contact as we had seen elsewhere, probably owing to a shortage of available water. What water there was probably originated from metamorphic reactions in crustal rocks — mainly from the micas.

Within the crustal rocks, a layer of highly metamorphosed gneiss next to the contact had been thoroughly dehydrated by one or more regional thermal events, in addition to any heating associated with the juxtaposition of the peridotite and the gneiss.

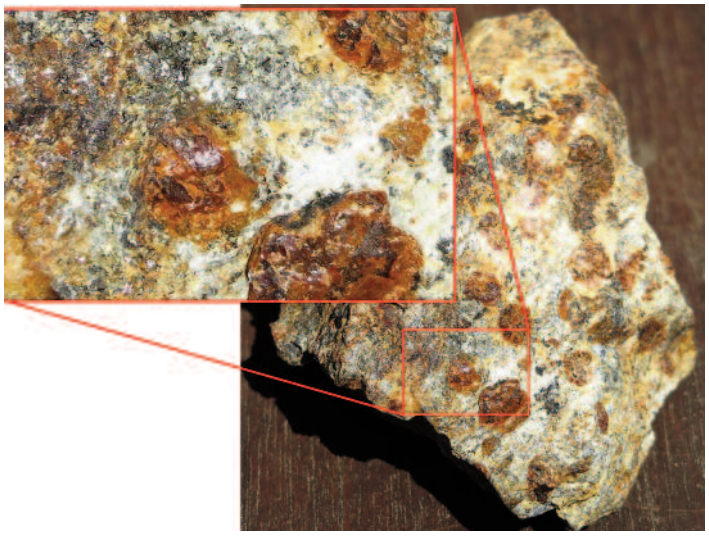


Figure 5.3 Kinzigite near the Alpujárride gneiss contact with peridotite near Pujerra. As an indication of scale. the largest garnets are c. *10mm across.*

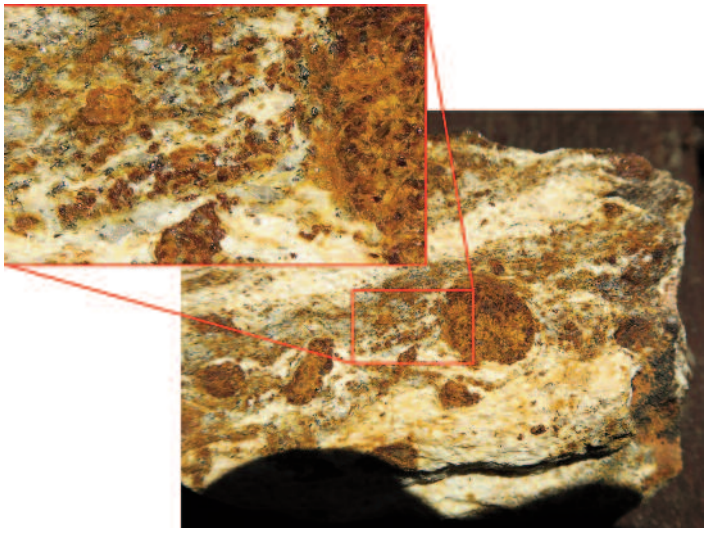


Figure 5.4 Granulite leucosome within the kinzigite, with quartz, feldspar, and some remnant biotite in the fabric. The largest garnet is c. *10mm across.*

What remained is a restitic rock called kinzigite (Fig. 5.3). Not only is it an attractive rock, dappled with garnets and glinting with graphite flecks, but it also encapsulates a lot of metamorphic petrology, revealing evidence of both prograde and retrograde metamorphism that probably reflect burial to the base of the crust, followed by exhumation. It contains abundant garnet porphyroblasts, some with included kyanite, the garnet being surrounded by a fabric of biotite + sillimanite + K-feldspar. Through the lens it was arguably possible to see cordierite formed as a rim reaction with biotite around the garnet, as well as kyanite pseudomorphs altered to sillimanite.

We also identified centimetre- to meter-scale light-coloured lenses of quartz and feldspar within the gneisses (Fig. 5.4); these are granulitic leucosomes, which imply that the regional thermal event heated the gneiss enough to partially melt it and dehydrate the micas, leaving behind only anhydrous minerals. The released water may have been assimilated into nearby leucocratic dykes, or used in serpentinisation of peridotite. Driving north-west from the contact, [36.598907, –5.142078] we moved into layers with significantly fewer garnets, the rocks grading through progressively lower Barrovian isograds. In the sillimanite zone, we were able to spot some sillimanite crystals (Fig. 5.5), as well as the much more ubiquitous fibrous form.

Figure 5.5 Sillimanite crystals in the gneiss, several hundred meters from the contact.

At our last stop in Igualeja (endowed with a much-needed bar for refreshment), we were back in limestone country where the River Genal emerges from a cave as a 'karst upwelling', according to a sign for visitors [36.632859, –5.118265].

Day 6 — Monday 4 May

Neo-Numidian flysch, Alozaina unit, peridotite/gneiss contact zone, Valtocado and gneisses in the Sierra Alpujata

Stuart Swales

Bidding farewell to Ronda, our convoy crossed eastwards over the Serranía de Ronda on the A-366 through a lovely landscape of pine forest and steep Jurassic and Cretaceous Subbetic carbonate hills, and through the village of El Burgo. South of El Burgo [36.774770, –4.937859] we stopped to examine a knoll of grey limestone. Within the mainly metre-scale beds of carbonate we observed thin beige-coloured, very finely laminated horizons, some containing organic-rich laminae, with faint traces suggestive of rootlets cutting *c.* 10mm or so down from the organic-rich laminae into the underlying sediment. The yellowish-beige layers have been interpreted as calcrete palaeosols, indicating cyclic emergence of the shallow-water carbonates (Fig. 6.1, *overleaf*). This whole block is an olistolith of Microcodium limestone, probably late Cretaceous to Palaeogene, within the Neo-Numidian flysch. Various theories have been proposed about the exact nature of Microcodium, one being that they are calcite structures secreted by symbiotic bacteria around mycorrhizal hairs.

Farther down the A-366, just south of the town of Alozaina, we stopped at an old bridge over a steep, deep arroyo, which has cut down through the Alozaina Formation (Miocene, earliest Aquitanian) [36.719891, –4.871557]. South of the bridge, the lowest part of the Alozaina Formation was seen to be a series of poorly sorted conglomerate and breccia beds, with randomly oriented clasts from millimetre up to metre scale, some very well rounded, others angular, in a poorly sorted matrix that ranged from silt up to medium sand grade. A number of the less chaotic beds could be seen to fine upwards and some of the beds appeared to be small channels. Silvery schist clasts contained black andalusite with rinds of alteration to muscovite — these are typical low-grade Alpujárride rocks, as were clasts with quartz veins that contained pink andalusite. All the clasts appear to be

Figure 6.1 Michael Perkins examining the yellowish-beige coloured layer of Microcodium Limestone at the first stop south of El Burgo.

derived from the directly underlying Maláguide and Alpujárride rocks. Tom pointed out the absence of any lower-level peridotites or higher-grade Alpujárride rocks here, even though they both are currently proximal to this deposit.

On the north bank of the arroyo the matrix was clearly coarser and more angular but the clasts themselves, while largely similar in composition to those across the arroyo, were smaller. One clast found there was typical lowest-grade Alpujárride, a high-sheen chloritic phyllite. We also found some smaller clasts of red sandstone.

Moving farther north to the new road-cutting, we found clasts with more feldspar, suggestive of derivation from a higher-grade Alpujárride source. As we walked north-east up the road-cut we observed clasts derived from metamorphic source rocks of increasing grade: we successively found small clasts with biotite and fibrolite, then sillimanite schists, some with hotter 'foxy' biotite (Fig. 6.2); then we found fibrolitic schists with albite/oligoclase feldspar porpyroblasts, eventually spotting migmatite clasts with strongly folded leucosomes and kinzigite clasts of deep origin. (An aside: Tom's illustrated word-of-the-day was faserkiesel: millimetre-scale quartz knots or pods containing fine sillimanite). This succession was seen to be covered everywhere by flysch in an angular unconformity. The flysch had what Tom described as a 'sensuous' — to the touch — fine matrix, breaking down readily to very coarse sand, which had periodically avalanched downslope forming mini-fans in the roadside drainage channel (Fig. 6.3, *opposite*) — an interesting parallel to the much larger-scale process in the deposit below!

The Alozaina Formation has been interpreted as a sequence of fast-flowing, mass-flow deposits from flash floods, and catastrophic rock-slides, into an extensional basin during the first episode of the collapse of the Alborán Domain. Zircons in the gneisses have been dated as growing in the middle crust at 21Ma — only just before their early Miocene exhumation. This relatively short roadside exposure is a spectacular witness to the progressive, yet rapid, unroofing of an orogen (Fig. 6.4, *opposite*).

South of Alhaurín el Grande we turned off the A7053 at Valtocado, parking by an entirely redundant roundabout [36.596173, –4.705536]. In road-cuttings just north of this location

Figure 6.2 A clast of sillimanite schist in the Alozaina Formation conglomerate; road-cut south east of Alozaina.

Figure 6.3 An example of a miniature avalanche forming a 'mini-fan' (scale is 100mm long; DMJ).

we could see brown migmatites with pale leucosomes sitting under a peridotite mass. This is a fault block of the Sierra Alpujata. Here we encountered our old friends, peridotite and gneiss, in close contact — a 20m or so wide chunk of gneiss was bounded to the north and south by seemingly little-altered peridotite with few thin serpentinite veins. At both boundaries the peridotite had altered to a yellow serpentinite. Freshly broken gneiss blocks found in the float were mid-grey with a strong foliation defined by a biotite fabric wrapping abundant plagioclase and K-feldspars — this was not the same as the 'lithoclastic gneiss' we had seen at our first peridotite/gneiss contact.

The southern boundary was sub-vertical, and within one metre of this boundary we could see the inclined foliation of the gneiss being progressively rotated to become aligned parallel with the boundary. Similarly, feldspars in the gneiss were seen to progressively thin and become extended in this ductile deformation. As the boundary was approached, a mylonite derived from the gneiss had no discernible feldspars, having been recrystallised, then a 20mm wide fault gouge composed of ground-up gneiss. However, at the northern boundary, subsequent multiple episodes of faulting had displaced the inclined junction and chunks of gneiss could be seen detached in this fault zone. In the nearby old road-cut, brittle faulting was seen perpendicular to the foliation (Fig. 6.5)

Figure 6.5 At Valtocado the southern contact between the gneiss body (left) and peridotite is relatively planar with the gneiss foliation stretched parallel to the contact plane. The gneiss is mylonitic at this contact; the yellow serpentinised gouge is derived from the peridotite.

Figure 6.4 We examined progressive Alpujárride exhumation during earliest Aquitanian in the Alozaina road-cut where clasts in the conglomerate went from lowest- to highest-grade in just 200m, indicating that the source rocks were progressively deeper as the area was unroofed.

Travelling onwards, we headed up the Guadalhorce valley to Álora, from where we went cross-country on the A-343 via Valle de Abdalajís, heading for our new base at Antequera. The countryside we passed through (no time for stops) was in the Early Miocene La Joya Olistostromic Complex, which seals the Internal / External Zone boundary and is stratigraphically above the Alozaina Formation seen earlier this day. This mélange has many

very large (individually map-able) olistoliths of Subbetic carbonates and flysch clastics, some being hundreds of metres in height and several square kilometres in area, hence the lumpy-bumpy appearance of the terrain!

More lovely scenery passed rapidly by, the road being flanked by more steep Jurassic and Cretaceous Subbetic limestone mountains. We had planned to return along this road the next day to look at the flysch and multi-coloured marls but it proved to be a bit too winding for some of the group, so we decided that we would not go back that way — we had actually seen enough from the cars!

Figure 7.1 View south from the top of the Sierra de Aguas. In the distance is the Sierra Alpujata (peridotite) with a quarry in the underlying marble at the left-hand end, above the town of Coín. In the middle distance the Sierra de la Roble is also peridotite, but with gneiss lower down below the houses (LF).

Day 7 — Tuesday 5 May

Sierra de Aguas peridotites (the smallest peridotite massif), gneisses, migmatites and granites

Caroline Deans

The car convoy set out from the Hotel Lozano in Antequera through a maze of roundabouts, up to the top of the town and out on the A-343 towards Álora. On the journey, thanks to the two-way radios, Tom interpreted the landscape for us, pointing out the relationship between the flysch and the peridotite massif and identifying the classic flysch landscape of green fields with their rocky olistrostrome exposures. These vary in size, from a few metres up to as big as 5km sandstone blocks. In the distance on the skyline we saw grey-brown flat-topped hills of Mid-Upper Miocene clastic sedimentary rocks.

At Álora we turned up into the hills, each with its castle. These hills are large blocks of Tortonian age set in the gentle farmland slopes of the flysch, which laps up to the pine-covered peridotite massif. As we climbed the tortuous road and then rough track, we stopped briefly to inspect white leucocratic dykes. At the summit view point [36.855202, –4.791515] we looked out towards Carratraca to the west; to the north-west a fault-bounded block of Jurassic limestone was marked by a wooded ridge and in the distance were cultivated fields overlying gneisses of the Aljibe unit, which in turn overlies the peridotite. In the far distance is a large olistostrome block of limestone. Looking south the different rock types stood out with their characteristic landscape, the peridotite close by and in the far distance. Sandwiched between them cultivated land and houses indicated the gneiss, phyllites and schists of the Alpujárride Complex and some superficial deposits (Fig. 7.1).

Next stop [36.853809, –4.812756], on a track off the road down to Carratraca (Fig. 7.2), we saw exposures of migmatite with shear zones of gneiss, separated into light and dark mineral layers containing garnets with tails which are kinematic indicators, indicating shearing and main foliation occurring at the same time as metamorphism (Fig. 7.3, *opposite*). These rocks were thinned and heated from below, as well as by the peridotite mass. Also there were shear zones cutting through the fabric: these were discrete shear sets, which deflected the foliation, indicating that the rock was half-way to being brittle. Pure shear flattening in mylonite zones is due to the north-east thrusting during the emplacement of the peridotite. We hoped to find kinzigite *in situ* but failed, although there was evidence in pebbles washed down from higher up the slope, and in the stream bed.

In the afternoon we investigated the Cerro Tajo fault [36.821643, –4.795731]. This is a major, later fault exposed in a high-sided road-cutting on the A-357 (Fig. 7.4, *opposite*): the gneiss is downthrown at the southern end and separated from peridotite to the north by fault gouge. We used the slickensides to give the direction of movement on the fault (smooth upwards, rough downwards on the gneiss), which indicated that this was a normal fault. The peridotite had been highly serpentinised, the fabric showed fault drag, as did a leucogranite dyke. The gneiss was rotting with

Figure 7.2 The migmatite and gneiss locality near Carratraca (LF).

Figure 7.3 Impromptu explanation of σ-type and δ-type shear by Tom. σ-type are porphyroclasts with wings of smeared off material; δ-type clasts are less common than sigma-clasts but good, unambiguous shear indicators. They develop from sigma-clasts when the clast rotates significantly (LF).

muscovite and chlorite present in cross-cutting veins; it contained garnets in the folded and twisted lenses, also chlorite, feldspar and quartz. The garnets were not the type associated with gneiss formation, so the fault was not an original contact between the peridotite and the gneiss, but rather a tectonic one. The peridotite contained large clasts of crustal gneiss, quartz and feldspar-rich with metasomatic rodingitised biotite due to Ca-rich fluids circulating during serpentinisation. This is a locality for the mineral xonotlite, a hydrous calcium silicate that occurs in serpentine and in contact zones (Fig. 7.5).

Our fourth stop was the *Arroyo de la Cala* (a different one from Day 2!) [36.810835, –4.782613]: at this location a peridotite-gneiss fault was examined, normal, brittle with serpentinisation between and around the fault. There were white bands of leucogranite dragged parallel to the fault. Quartz veins were

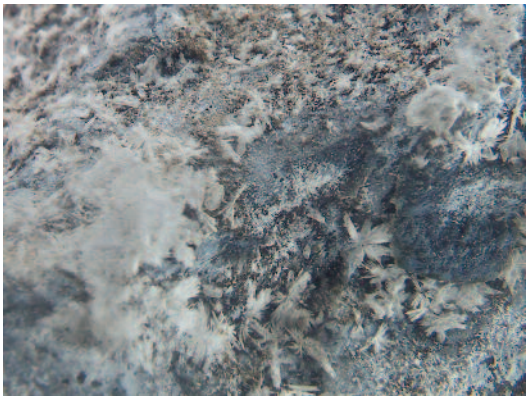


Figure 7.5 Very rare acicular xonotlite crystals on serpentinised peridotite (largest crystal 3mm) found at the Cerro Tajo fault. Xonotlite is a hydrous calcium silicate ($Ca^6Si^6O^{17}(OH)^2$), which occurs in the late veinlets associated with the cordierite granitic dykes from the Ronda peridotites. The presence of xonotlite is typical of the rodingitisation process, which caused Ca-metasomatism of the granitic dykes during serpentinisation. This mineral is found in less than 20 localities across Europe so it was great pleasure seeing it in hand specimen (SC).

Figure 7.4 The Cerro Tajo fault exposed in a road-cutting on the south-west side of the A-357 south of Carratraca (LF).

present in the peridotite, similarly deformed, also some large garnets. Large almandine garnets were present in the kinzigite, while there were small, abundant, Mg-rich spessartine garnets, together with tourmaline, in the leucogranite, which grew in the melt. These indicate S-granite (crustal melt) with a marine sedimentary origin, which was then metamorphosed and migmatised (Fig. 7.6).

We made a final stop on the A-357 just south of Carratraca at the *Punto de interes geologico — Sierra de Alcaparaín*, one of the stops on the Guadalteba *Ruta Geológica*. This was between two peridotite blocks, which showed lots of deformation, clearly seen in the white leucogranite and quartzite veins, which were intruded while the host rocks were still undergoing deformation.

Figure 7.6 Large almandine and smaller spessartine garnets at Arroyo de la Cala (LF).

Day 8 — Wednesday 6 May

Sierra de Aguas cover, metamorphic schists, phyllites and lower-grade lithologies

Paul Speak

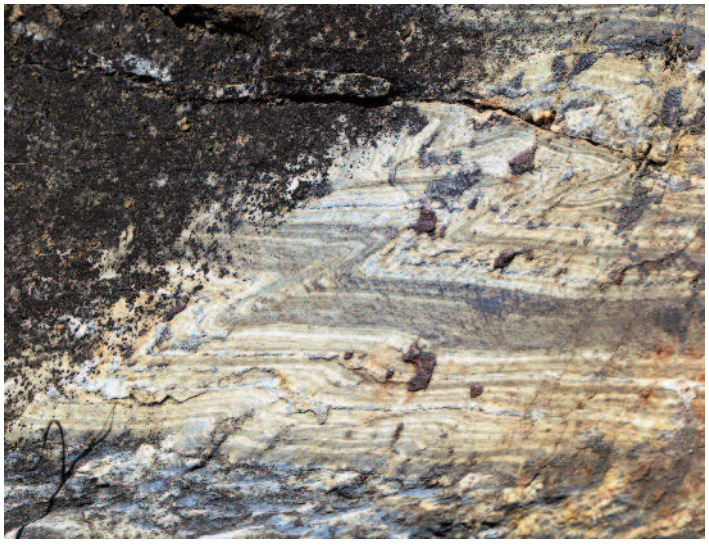
We headed towards Ardales and then took the MA444 east towards the reservoir to the first stop at the *Arroyo de la Zahuda* [36.896847, –4.826426] to walk up a section of Palaeozoic and Mesozoic sediments, part of the Maláguide nappe.

A road-cut near the bridge revealed greyish-white Upper Cretaceous (Cenomanian/Turonian) marls, dipping north. It comprised fine-grained carbonates and clays with no visible fossils, suggesting a shallow marine platform environment. The description 'pretty well mashed up' summed it up, with signs of ductile deformation before brittle fracturing. There was no sign of any lower Cretaceous rocks, which may have been eroded or not deposited here. Across the arroyo, on the ridge, were exposures of the underlying mid-Jurassic limestones, also dipping north. While the Cretaceous marls were much deformed, the more competent Jurassic limestones were not.

We walked up the arroyo, soon reaching a series of Triassic red beds: a variety of mature conglomerates consisting of rounded clasts of sandstone pebbles and much quartz, as well as terrestrial sandstones and mudstones. This suggested a wadi-type depositional environment with flash floods. Also visible were a series of red marls, indicating an oxidised state with ferrous Fe(III) iron. There were pale green spots and bands caused where organic matter had been broken down by oxygen-scavenging bacteria, which reduced the Fe(III) to Fe(II). We also found a caliche layer: a hard pan formed by calcareous concretions below the surface. Suggested environments included a palaeosol or a coastal lagoon.

Continuing up the arroyo, and hence down the stratigraphic sequence into the Carboniferous, the next exposure was a grey, gravelly conglomerate interbedded with siltstones and fine sandstones; there were no fossils, but there was some evidence of cross-stratification. Faulting and warping of the finer sediments gave evidence of deformation. The bedding was very steep, much more so than in the Triassic beds. The stratigraphic column supplied in our field notes indicated an unconformity in the area. A weak tectonic fabric was detected in the conglomerate, with a spaced dissolution cleavage. This was thought to be related to the Variscan Orogeny, as it was not detected in the later Triassic-Cretaceous strata.

Figure 8.1 Z-fold in phyllite, offset c. *50mm.*



After lunch in a pine forest we drove on to a nearby bar for coffees etc. and noticed lots of Griffon Vultures; about 25 sat on a ledge some 60m above the bar while another 50 or so circled above the ridge. A pale yellow gecko came out of its hiding-place under the roof to observe the proceedings.

We then continued east to the *Arroyo de Colmenar* [36.894578, –4.752534]. As the temperature continued to rise we walked down a track to the river, disturbing a Great Egret from its feeding spot. Under the road and a little way up the arroyo, the first exposure was a grey rock with much small-scale folding, containing biotite and small garnets. It is a strongly foliated phyllite with visible bedding, which picked out beautiful Z-folds, all verging to the north-east as might be expected in the Alpujárride nappe (Fig. 8.1).

Another 50m up the dry arroyo we found small garnets in sandy layers with andalusite in the more pelitic layers. Farther along there was some evidence of staurolite with garnets in the schists. This evidence all indicates that the metamorphic grade increases farther down the succession, confirmed by finding fibrous sillimanite farther along. Sam found a large (*c.* 20mm) pink andalusite crystal in the scree beneath a higher exposure (Fig. 8.2).

Figure 8.2 Andalusite crystal found by Sam Capstick (SC).

Close examination revealed that the garnets were pre-tectonic (the foliation wraps around them), the biotite and sillimanite were syn-tectonic and the andalusite post-tectonic as the crystals are randomly oriented and overgrow the tectonic foliation. The interpretation is that, as the crust thinned, the hot mantle got closer, increasing the metamorphic grade. In quartz veins near the top of the arroyo, early (deformed) kyanite crystals were found, some replaced by later andalusite.

Returning the way we had come, a convenient lay-by [36.910369, –4.767218] gave us a good view towards the *Desfiladero de los Gaitanes*, the spectacular gorge near El Chorro (Fig. 8.3, *opposite*). We noted that there were large outcrops of vertically bedded limestone visible to the south-east, close to the sub-horizontal sediments on which the Griffon Vultures were perched. The contact could not be seen, but it was described as a vertical unconformity, where the Betic deformation had folded the limestones into vertical structures, which later became a sea cliff. The later Tortonian or Messinian high-energy marine sediments were laid down horizontally against the cliff in a shallow marine basin. This was thought to have been one of the last narrow seaways from the Atlantic to the Mediterranean (Martín *et al.* 2001).

Figure 8.3 The Desfiladero de los Gaitanes, eroded through the vertical bed of limestone (LF).

Day 9 — Thursday 7 May

Málaga dykes; El Torcal de Antequera-Dorsale unit limestones

Michael Perkins

Following on from the previous day's excursion to the Ardales area, our morning locality in the Guadalmedina Valley enabled us to inspect a different relationship between the Maláguide unit and younger rocks. After driving south from Antequera and parking the cars by the A-45 junction just south of Casabermeja, we walked some 200m up a side road with some excellent exposure on its northern side [36.879575, –4.427819]. Here we could see some fine-grained rocks with a well-developed cleavage. Before long, though, we found a different lithology: a clearly crystalline unit, which cut diagonally upwards to the west through the country rock.

This dyke appeared to be composed of several distinct units, perhaps corresponding to multiple intrusion events. The unit farthest to the west remained relatively fresh. The next was very badly weathered to a brown colour, while the right-most unit before the country rock was again less altered. Faults were seen to cut the dykes and country rock, offsetting the contacts. The fresher rock showed no fabric (suggesting that the intrusion was subsequent to metamorphism of the country rock) and appeared to contain abundant white feldspar and putative amphibole. Studies on the rock have confirmed a tholeiitic composition, containing hornblende and pyroxene, with an Ar-Ar date of 23Ma that places them at the end of the Oligocene.

The boundaries of the intrusion revealed two things. Firstly, the intrusion cut cleanly across the fabric of the country rock. Secondly, a chilled margin could be discerned, and the country rock appeared to be baked, implying intrusion at relatively shallow crustal levels (Fig. 9.1). These rocks have provided insight into regional tectonics, since measurement of the magnetic orientation locked into component minerals at the time of crystallisation indicates that the area has undergone clockwise rotation by up to 130˚ since emplacement. The intrusive material itself probably originated from a mantle partial melt associated with a thermal pulse resulting from the hypothesised mantle delamination event.

Walking a little farther up the track gave us an excellent opportunity to identify shear sense indicators within the Maláguide (Fig. 9.2, *overleaf*). These rocks are Palaeozoic in age, with the fabric most likely representing the Variscan orogenic event, and metamorphic minerals are limited to chlorite and white mica. The rocks are filled with strongly folded quartz veins. With Tom's help, we identified quartz veins that pinched out parallel to the fabric where, in some cases, the fold hinges have detached completely to form lozenges (Fig. 9.3, *overleaf*). We also found conjugate fracture sets, cutting through the Maláguide fabric. Stretching lineations could be found on some surfaces, while Tom explained how we might distinguish these from similar bedding-cleavage intersection lineations or wavier crenulation lineations.

Figure 9.1. The contact between the Oligocene dyke and the Palaeozoic Maláguide country rock.

Figure 9.2. Tom explains various shear sense indicators. From top, left to right: folded quartz veins thicken in the hinge and thin parallel to cleavage; quartz lozenges where thickened fold hinges become detached; more competent beds form lozenges or fold boudins; foliation becomes boudinaged, with quartz in-filled in boudin neck; shear fractures form a conjugate set; wavy crenulation lineations (left) and straighter stretching lineations (right).

We drove across country, through Villanueva de la Concepción, to reach our afternoon stop, which was a leisurely excursion to the *Paraje Natural* (Protected Natural Site) of *El Torcal de Antequera* [36.952532, –4.545014]. A *Torcal* is an area where *torcas*, or *dolines*, are found, circular depressions around sink holes in karst. The *Torcal* of Antequera comprises a Subbetic Jurassic limestone massif rising to more than 1,300m, some 700m above the town, and is rightly famous for its spectacular karstic landscape, a product of the erosion of the sub-horizontal beds of limestone. This is most dramatically displayed in the national monument *El Tornillo*, named for its resemblance to a screw (Fig. 9.4).

Our group split up to be free to explore the park at our leisure (and to try to avoid the bus-loads of school children!). In fact, it does not take a long walk to find tranquil spots, even on the well-trodden paths that lead off from the information centre. My group explored the yellow path, which winds its way 3km into the park and takes in spectacular scenery including overhanging cliffs, caves, platforms and gullies.

The differential erosion of the limestone, giving rise to the 'stacked-pancake' landscape, is formed by the different solubility of the component beds. These beds comprise oolites, pseudo-breccia beds (these are partially dolomitised to give a brecciated appearance), nodular beds and more massive units. Each lithology is eroded and dissolved in a distinctive manner, producing a landscape of many contrasts (Fig. 9.5, *opposite*).

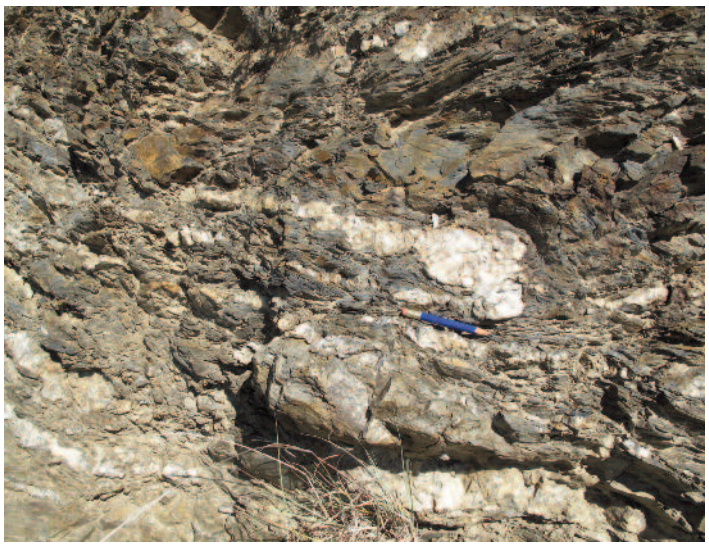


Figure 9.3. Folding of the quartz veins, thinning or pinching out parallel to the metamorphic fabric.

Most of the beds are not fossiliferous to the naked eye. However, there are some exposures of the *ammonitico rosso* bed, distinctive for its nodules and mottled pink tones. My group found two ammonites of different sizes (one c. 200mm diameter, the other about 5mm), and abundant belemnites. Other groups found other marine fossils including coral, crinoid stems, bivalves and bryozoa (Fig. 9.6, *opposite, and page 108*).

Day 10 — Friday 8 May

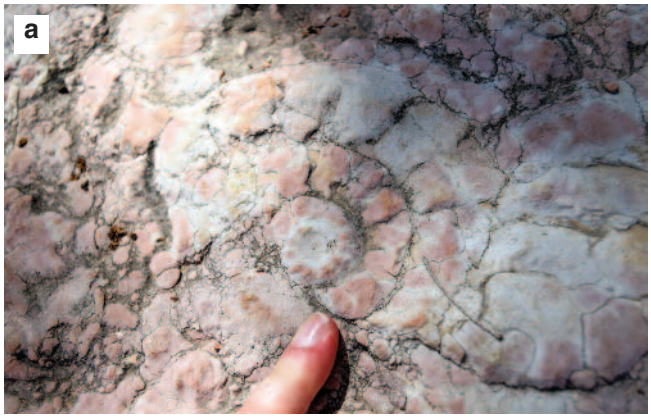
Morning: Sightseeing in Antequera

Chris Hodgson

Before setting off for Granada, the group took the opportunity to visit the nearby archaeological site of the *Viera* and *Menga* dolmens. Local geology contributed to favourable conditions for prehistoric settlement: the Antequera Basin was one of the late Miocene embayments along the southern edge of the Guadalquivir Basin. It became filled mostly by platform temperate carbonates and mixed siliciclastic-carbonate deposits interfingering laterally with basinal marls. With later flysch deposits and some uplift, a low lying plain with a river network developed in the area of the present town of Antequera.

Figure 9.4. El Tornillo *('The Screw'), an eroded tower in the Jurassic limestone of El Torcal. (*https:// apbvigo.wordpress.com/2014/04/22/ el-tornillo-torcal-de-antequera/_4140452-od/ *under Creative Commons Licence).*

Figure 9.5. The landscape of El Torcal.



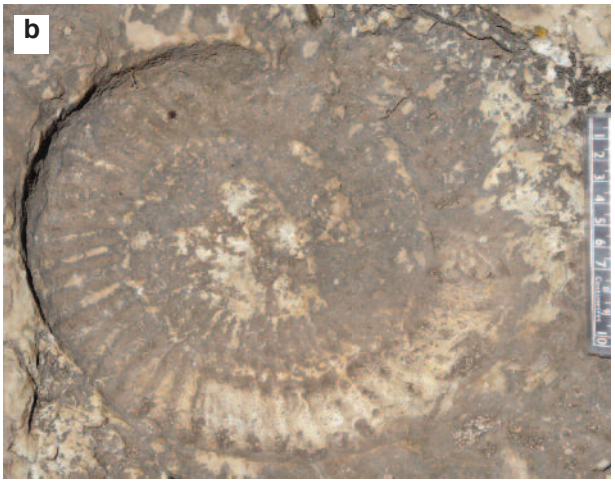


Figure 9.6. Fossiliferous horizons in the limestone of El Torcal yielded: ammonites (a – MF; b–d – DMJ), (e) belemnites (MP) and (f) crinoids (MP/DMJ).

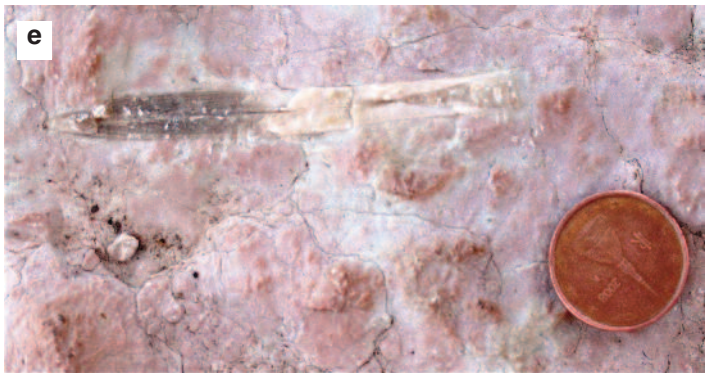


Figure 9.6 (cont'd) (e) belemnite (MP) and (f) crinoid (MP/DMJ).

The fertile soil conditions in Antequera, coupled with the warm wet prehistoric climate, plus availability of timber for shelter to augment the many surrounding cave dwellings (*El Torcal de Antequera, La Peña de los Enamorados*, etc), encouraged human habitation. These Neolithic structures were probably erected between the end of the 4th and the beginning of the 3rd millennium BC (carbon dating). They were not built as astronomical observatories, although they do suggest astrological interest; rather they were community ritual gathering places. For these animist societies death was just another rite of passage and skeletal remains and grave goods are found in megalithic buildings.

The Archaeological Site, on a small hill near our hotel, protects the Viera and Menga dolmens, correctly so called, as they are corridor tombs. Their substantial covering creates the domed tumuli still seen today (Fig. 10.1). From the *El Caminante* 'Observatory', we could appreciate the spatial relationship between natural formations of the surrounding countryside and the tumuli. The linked 'Solar Centre' shows the orientations of the most important dolmens of the Iberian Peninsula. Most European megalithic monuments have their entrances oriented more or less to the summer sunrise. Here Viera follows this pattern whereas Menga faces north.

Figure 10.1 A domed tumulus covers the Viera dolmen. The iconic limestone peak, La Peña de los Enamorados, towards which the Menga dolmen is orientated is seen in the distance (DMJ).

The main building stone required was near by: we could see the disused hillside quarry believed to be the source. Blocks were quarried using fire and water; they were cut and shaped using flint tools and transported on rollers to the prepared site. The orthostats (uprights) were raised up ramps (which could later become the base of the tomb covering) and manoeuvred to fall into position in the cut channel dug down to the bedrock. The slabs were made vertical, wedged in place with boulders and stabilised. We noted their precision fit, with only a few wedges and filling blocks used, and no mortar (Fig. 10.2). Additionally in Menga, central pillars were also emplaced (*see below* and Fig. 10.3, *opposite*). The whole interior would then have been filled with rubble up to the height of the orthostats to enable roofing with capstones before clearing the internal space and completing the tumuli with layers of various materials, including rocks and minerals brought from a distance. Domes were up to 50m diameter and 15m high. At this site the domes have been seeded with plant species identified by analysing Neolithic pollen.

At the ruined entrance to the Viera dolmen, missing capstones allowed enough light to study an orthostat decorated with cavities known as 'cups', a common motif in Iberian prehistoric art. Lying on the floor was part of one door and farther inside was 'hinge' evidence of another. The doors and dimensions of the corridor would symbolically prolong the passage to the burial chamber. Essential restoration, for safe access, involved replacing some missing capstones, but the final quadrangular chamber is the completely original funerary area.

Figure 10.2 Careful fitting and packing of stones, Menga dolmen (DMJ).

Figure 10.3 Line of supporting pillars along the central axis of the Menga dolmen (DMJ).

The Menga dolmen did not fail to impress. The trapezoidal shaped, unroofed atrium fronts the iconic trilithon (Fig. 10.4). This inner part of the lintel-like construction is unparalleled in the Iberian Peninsula. The 250-ton capstone is one of the two that originally covered the entrance corridor (2.5m wide and 2.7m high, 6m long). Following into the funerary chamber (6m wide and to 3.5m height at the head, 20m long) there are four similarly huge blocks spanning the roof between 13 orthostats. A very unusual feature in European megalithic structures is the presence of internal pillars as found here. Three large pillars are aligned along this chamber's longitudinal axis (*see* Fig. 10.3). As these coincide with the joins of the four capstones it seems likely they were to installed support the roof. The lower parts of the pillars are slimmer and although the medium-grained sandstone appears well cemented, later abrasion could be responsible. Still visible on one orthostat are more typical motifs of megalithic art: cruciform shapes and star-shaped engravings in the coarse-grained, gritty, sandstone.

The final amazement of this monument is the view looking out of the dolmen — a direct view of the famous hill that resembles a recumbent head, *La Peña de los Enamorados* (Fig. 10.5). We did not visit the nearby, later, dolmen of *El Romeral*, which has an equally interesting and unusual alignment towards the high-point of *La Sierra del Torca*l.

Figure 10.4 Entrance to Menga dolmen, showing trilithon (DMJ); inset, Dr Jones atop the dolmen, for scale (CH).

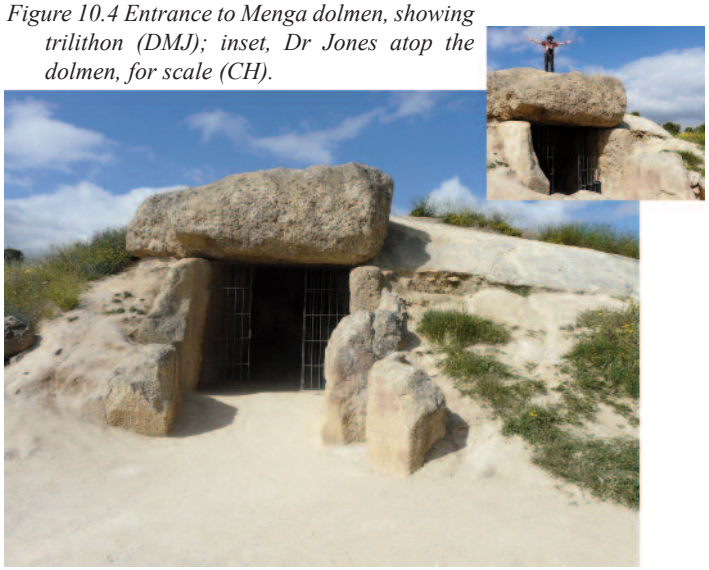


Figure 10.5 La Peña de los Enamorados, the peak from which a pair of lovers, a Moorish princess and a Christian man are said to have escaped capture by leaping to their deaths. It is also known as the Montaña del Indio because of its supposed resemblance to a sleeping Native American's face (DMJ).

Day 11 — Saturday 9 May

Sierra Nevada metamorphic rocks

Linda Fowler

A drive up the A-395 Sierra Nevada road gave us several opportunities to examine rocks of the Nevado-Filabrides Complex, which dominates this range of mountains as well as the Sierra de los Filabres.

We first stopped a short way uphill from a *Jardín Botánico* parking area [37.112060, –3.431919]. Up to this point we had noticed roadside exposures of Triassic carbonates of the Alpujárride nappe, but now found schist of the Palaeozoic/Triassic Mulhacen Complex — because of the geometry of the thrust sheets, as we drove uphill we were moving down the sequence into older rocks. Structurally above the schists we observed carbonate rocks with patches of a white, acicular mineral, which at first glance looked like some kind of vegetation. Further inspection showed this to be gypsum in the satin-spar type of habit in which fibres grow in parallel. In this case the fibres were very coarse, 2–4mm in thickness and up to 300mm in length (Fig. 11.1).

Figure 11.1 Satin spar gypsum at first stop, walking pole for scale (LF).

Bernard Skillerne de Bristow

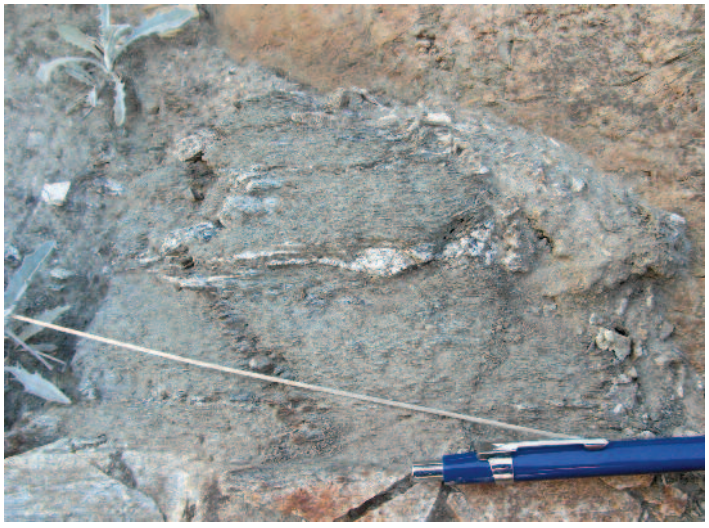
We drove on uphill and examined a roadside section [37.098258, –3.390624], where we found a sequence of pelitic schists and leucogranites of the Proterozoic/Palaeozoic Veleta Complex. The pelites contained a Grt+St?+Pl+Qtz assemblage typical of lower amphibolite facies, but only the garnet was clearly identifiable; we only saw the staurolite as occasional stubby brown prismatic crystals. Texturally, the leucogranite was highly sheared with a proto-mylonitic fabric, which had overprinted the original igneous texture (Fig. 11.2); it contained tourmaline similar to that seen on previous days. The most spectacular feature of the exposure was the range of microstructures. This included σ-type (Fig. 11.3) and δ-type (Fig. 11.4) chlorite-mantled porphyroclasts, which can be used as kinematic indicators, and foliation boudinage (Fig. 11.5, *opposite*). Isolated fold hinges showed that the rocks had been isoclinally folded. A later series of tight upright folds have folded the F1 foliation and produced a well-developed stretching lineation parallel to the F2 axial plane. This suggests that the maximum transport direction is not given by the vergence of the folds.

We had hoped to see evidence of the mafic/ultramafic body that has been interpreted as a disrupted eclogitised ophiolite but this

Figure 11.2 Sheared protomylonitic fabric in leucogranite overprinting original igneous texture at second stop.

was not evident in the road section. Later in the afternoon three of us returned to the locality and looked at the rocks in the hill above the road. There we found a strongly magnetic, green garnet-bearing rock that appeared to be of high density, which we tentatively identified as a pod of the disrupted eclogite, and which had been subject to significant retrograde metamorphism.

Figure 11.3 (above) σ-type kinematic indicator seen at second stop.
Figure 11.4 (below) δ-type kinematic indicator seen at second stop.



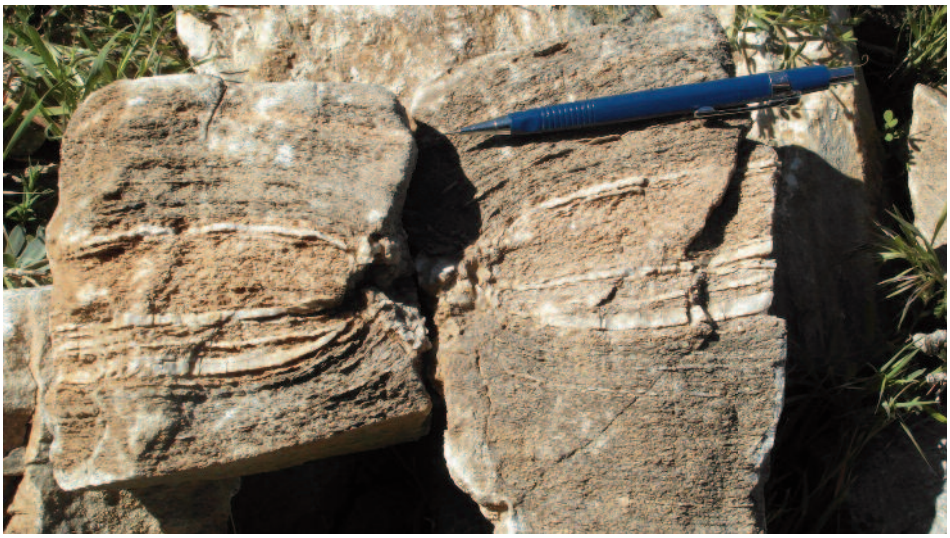


Figure 11.5 Boudinaged foliation seen at the second stop.

Day 12 — Sunday 10 May

Nigüelas Fault; Padul Basin; Nerja conglomerates; Torrox gneiss

Bernard Skillerne de Bristow

We had not realised that our last day in the Betics was the Geological Society of Spain's (SGE) *Geolodía* ('Geology Day'), when they organise events across the country for the general public. Our visit to the Nigüelas Fault coincided with one of these events.

As we drove to Nigüelas we got good views of the Granada Basin (Fig. 12.1) This is one of the many Neogene sedimentary basins that have formed around the Betics during the later stages of orogenesis at around the same time as the thrusting in the External Zone, extensional thinning of the Alborán Domain units, and subduction/exhumation of the Nevado-Filábride Complex. The sediments within the Granada Basin are flat-lying and are fault-bounded with the sediments on-lapping the fault surfaces. Only the youngest sediments are seen at surface outcrop.

We parked above Nigüelas village [36.982136, –3.536371] and close to the parking area we could see a small fault bounded rift that has formed on this eastern edge of the Granada Basin (Fig. 12.2, *overleaf*) The Nigüelas Fault lies close to one side of this rift and is one of the bounding normal faults of the Granada Basin. It dips inward at an angle of *c.* 40–45° degrees, south-west towards the centre of the basin, and the fault plane is well exposed as a polished surface with well-defined slickensides (Fig. 12.3, *overleaf*). In Figure 12.4 *(overleaf)* it can be seen that the overlying sediments dip in towards the fault plane. This could suggest that the fault is listric at depth and that sedimentation was syntectonic, resulting in a thickened wedge of sediment close to the fault. Alternatively, or in addition, the originally flat-lying basinal sediments could have undergone extension, resulting in an anticlinal roll-over fold with it axis running parallel with the fault.

In the car park where we stopped to see this fault, Professor Jose Benavente and Dr Carlos Sanz de Galdeano (geologists from the University of Granada) were setting up mirror stereoscopes to enable the public to view aerial photographic pairs (Fig. 12.5, *page 113*). We introduced ourselves and were kindly invited to join in! Photo-geology has gone a bit out of fashion these days, but it is still a valuable tool for regional geological mapping.

Figure 12.1 View of the Granada Basin: flat lying sediments are bounded by steep fault contacts with the older rocks of the Sierra Nevada.

Figure 12.2 At Nigüelas the main fault at the basin edge is cut by a small fault bounded rift running east–west into the Granada Basin.

Figure 12.4 Syntectonic sediments dipping in towards the Nigüelas fault plane with onlap.

Using pairs of photographs that partially overlap, the minor stereoscope enables us to see the topography of the fault area in 3D. Geological features such as bedding planes and faults could be easily recognised. Dr Sanz de Galdeano was also kind enough to send two images of the area (Fig. 12.6(a), *opposite*, (b) and (c), *page 114*) to use in this account.

We broke for lunch in Nerja on the coast where some of the group took the opportunity to inspect exposures of Pleistocene conglomerate on the beach (Fig. 12.7, *page 114)* [36.746470, –3.872575].

Our final stop was to see the Torrox gneiss exposed in a road-cutting on an abandoned housing development. The Torrox gneiss complex is a heterogeneous gneissic body that is located in the central segment of the Betic Cordilleras *c.* 50km east of Málaga. It is stratigraphically at the base of the Alpujárride Complex in this area, beneath a thick sequence of amphibolite facies graphitic schists. The latest metamorphic/deformational event has resulted in a mylonitic fabric (D2). The age of the unit and the date of the metamorphism are uncertain. Some data appear to support Variscan deformation, while others Alpine. It is also possible that this was a Variscan tract that has been reworked during the Alpine Orogeny. Mineral assemblage data from the overlying schists suggests Barrovian metamorphism with a clockwise rotation of the PTt path.(Garcia-Casco *et al.* 1993). Micro-diamond inclusions have been found in the garnet indicating that the rocks have suffered ultra-high pressure metamorphism (Coleman and Wang 1995). As the presence of diamond requires pressures equivalent to a depth of burial of 120–150km it is generally thought that the presence of diamond indicates that crustal rocks must have been subducted to these depths and rapidly exhumed.

Figure 12.3 The impressively steep, polished Nigüelas fault plane provided a slide for young geologists.

Within the Torrox gneiss itself, the main rock type is a medium-grained granitic leucogneiss containing Qtz+Na–Plag+Kfd+Ms+Bi with accessory minerals such as tourmaline typical of S-type granites. The gneiss is migmatic and contains cm-scale enclaves of aluminous minerals, which are interpreted as restites. Owing to the complex nature of the deformation and partial melting, the origin of the Torrox gneiss is uncertain (Fig. 12.8, *overleaf*).

Conclusion

We arrived back in Málaga on Sunday evening, at the Málaga Nostrum hotel close to the airport, and enjoyed using their outside bar area for the final debriefing before having dinner together and thanking Tom for leading such an excellent trip, and Jan who had organised it so meticulously (with some back up from Linda). All that remained was a final run to the airport in the morning to fill up with fuel, return cars and to check in for flights home when, hopefully, some of the group were able to appreciate the countryside from the air that they had so recently explored on the ground!

Figure 12.5 Mirror stereoscopes being used by staff from Granada University to demonstrate 3D stereo models of the Nigüelas Fault.

Figure 12.6 (a), (b) (overleaf) and (c) (overleaf) The Nigüelas or Padul-Dúrcal Fault — distant and aerial views. The line of the fault can be easily followed and also the alluvial fans. The rocks in which the quarries are situated are Alpine marbles (former Triassic carbonates) and belong to the Alpujárride Complex. The snow-covered rocks of the Nevado-Filabride Complex, mainly dark schists and quartzites. Tectonically, the Nevado Filabride is under the Alpujárride Complex. The high peak (centre-left) is 'El Caballo' (photos – courtesy of Dr Carlos Sanz de Galdeano Equiza, University of Granada).

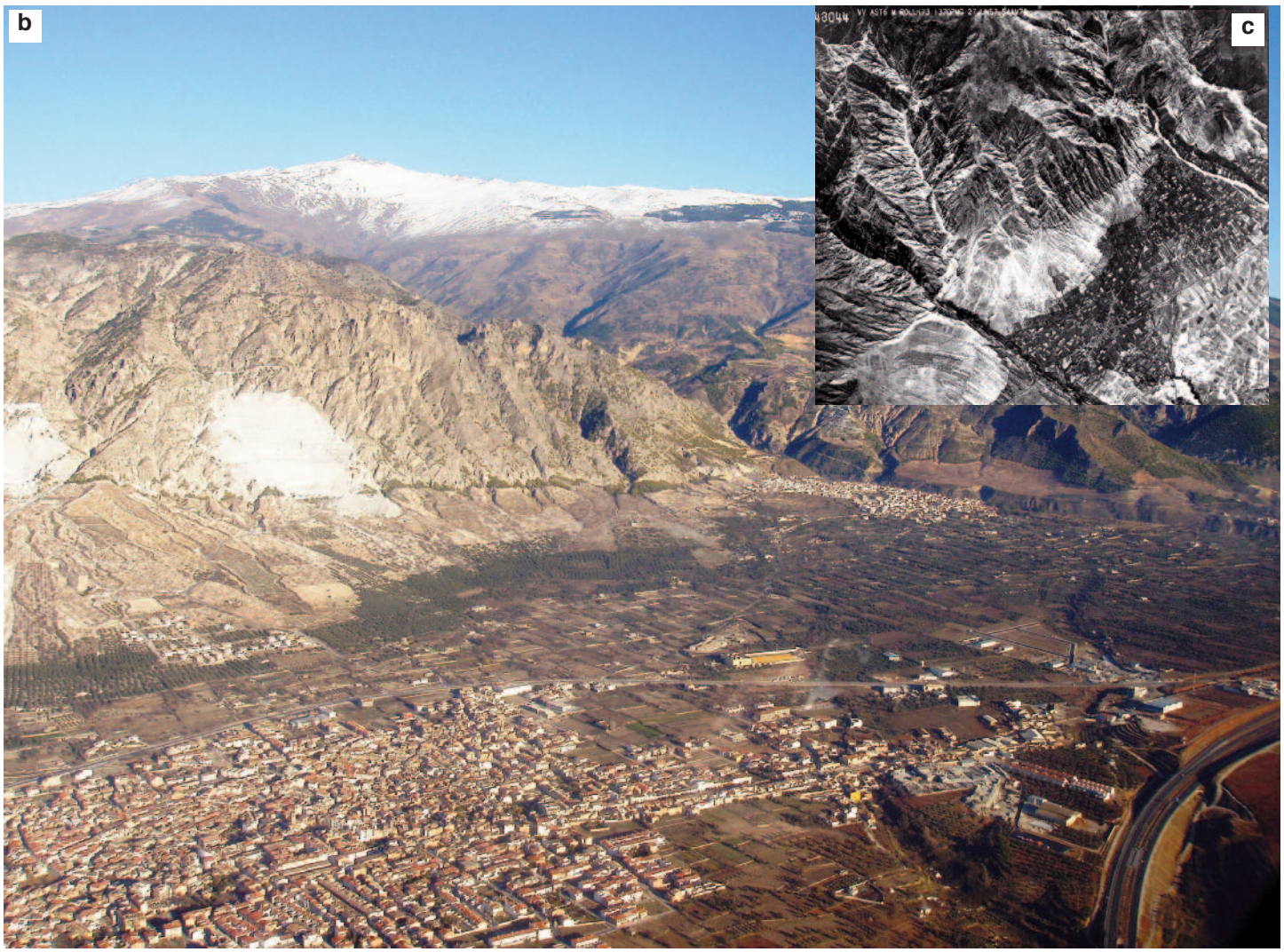


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Figure 12.7 Pleistocene conglomerate exposed in sea cliffs at Nerja: marble pebbles in a hard, well-cemented matrix, deposited in alluvial fans sourced from the north (LF).

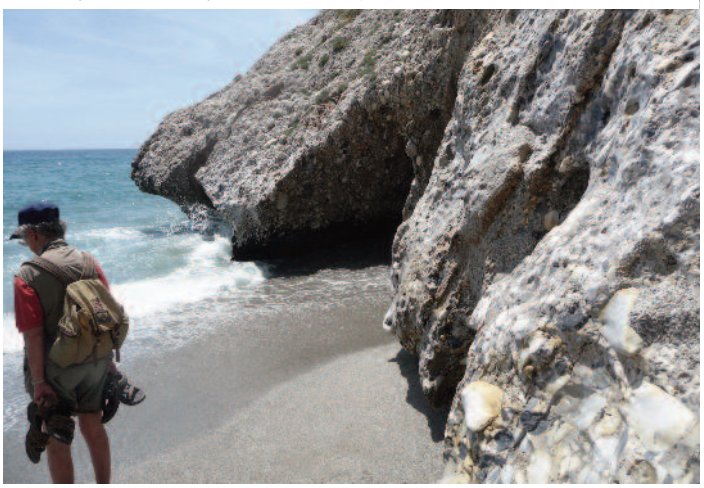

Figure 12.8 Tom examines a pod of folded gneiss between flat dipping mylonite zones, which were developed during a period of heterogeneous deformation by simple shear (LF).

Chapel Hill, Torquay

Richard Blagden, Martin Broadbent, Annie Kitto, Gina Little and Trevor Ryder

Introduction

This field guide has been put together by a small group of current and former undergraduate Earth Science students from the Open University. In June 2015 we visited Chapel Hill on an OU Geological Society field trip to explore the site and to practise our field skills, and this guide has been put together as a result of our work. Unless referenced otherwise, the work here is the result of primary research and we welcome any feedback that would improve it. Please note that no risk assessment is provided and if you wish to use this guide to explore the site you will need to make your own common-sense assessment of the risks involved (Richard Blagden, editor: rich.blagden@icloud.com).

Site overview

Chapel Hill (OS grid reference SX9065) is a small geological site situated about 1km from the centre of Torquay (Fig. 1). The English Riviera was designated as a Global Geopark in 2007 (English Riviera Geopark 2015a). Chapel Hill is one of its geosites, and is also designated as a County Geological Site (CGS) and as a Regionally Important Geological Site (RIGS) (English Riviera Geopark 2015b). It is noted for its Devonian limestone and Permian breccia, and for the relationship between the two (English Riviera Geopark 2015b), and is known locally for the *c*. 13–14th century chapel, St Michael's, that tops the limestone (Fig. 2; Crowson 2015).

Figure 1 Sketch map of Chapel Hill — OS grid reference SX9065 (Martin Broadbent).

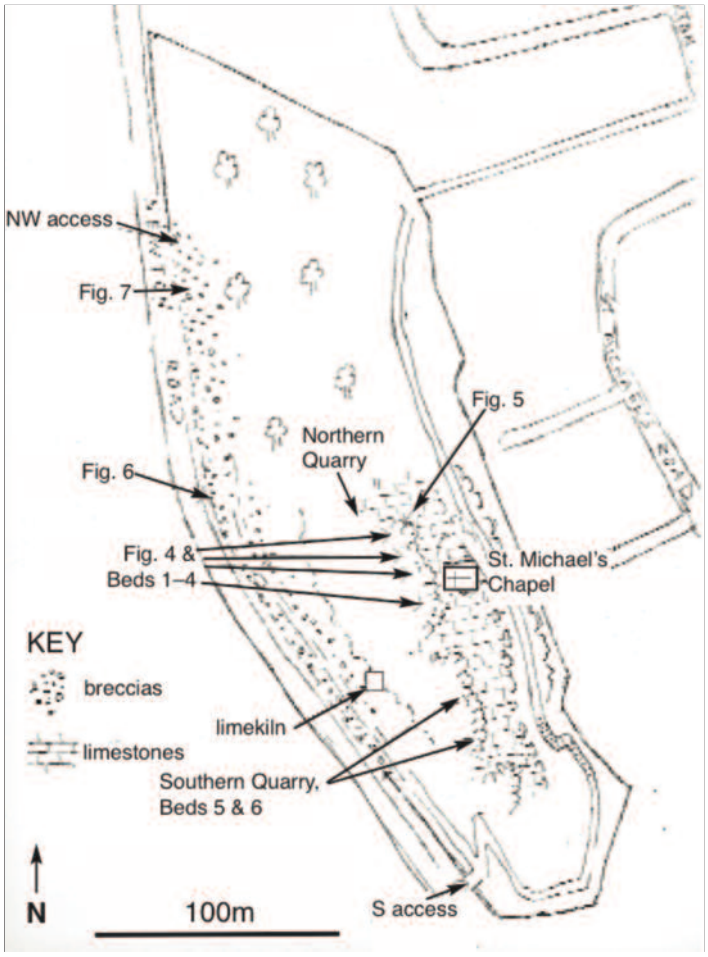

Figure 2 St Michael's, Chapel Hill.

It is a small urban site measuring *c.* 400m by 100m along a north–south axis, and consists of steep-sided woodland. Recently Torbay Council has begun a three-year management plan of thinning non-native trees to improve access to the geology and views from the chapel (Herald Express 2015). Very little has been written about Chapel Hill in the geological literature and the exact position of the limestone within the local stratigraphy is open to conjecture. The British Geological Survey map (BGS 2004) marks the locality as part of the Nordon Formation, more specifically one of two possible strata either side of the Marldon Limestone Member. We did not feel that it would be time-efficient, or within our skill set, to attempt to tie the limestone down to a narrower time period than this. The limestone itself has been extensively quarried on its western side.

The source of the Permian breccia that abut the western side of the limestones is clearer. The Sticklepath Fault runs underneath Torre railway station immediately to the west of the site (BGS 2004) and this has moved breccia that was originally several kilometres to the south-east to rest alongside these limestones. It is believed that the contact is fault-controlled (English Riviera Geopark 2015b). However, our survey of the site did not reveal anywhere we could definitively see the contact between the two rock types so we were unable to confirm this.

Visitor information

Although the busy A3022 passes directly to the west, the closest parking is on the opposite side of the site, near the north-east entrance, on Barton Road and other nearby streets. Torre railway station is 50m from the south-west entrance to the site and near the north-west entrance there is a bus stop for the No. 12 service, which runs from Newton Abbot to Torquay, Paignton and Brixham regularly through the daytime. There are no public toilets near by; cafés and shops are *c.* 1km from the site in Torre.

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Devonian Limestone

We started work at the northern end of the quarry (Face 1) and were able to identify a bedding plane by the presence of stromatoporoids. From here we worked upwards through the succession and recorded details of six surfaces in total. The succession is massively bedded and rather featureless, and bedding planes were identified for the most part by coincidence of angle of dip. Although the rocks had recently been cleared of vegetation the surfaces were well weathered (more so towards the southern end) and some hammering was needed to reveal the detail. Hand lenses were used to identify fossils. Table 1 summarises each of the beds studied.

Table 1

Bed	*Vertical distance (from Bed 1)**	*Dip*	*Notes*
1	N/A	60º SW	stomatoporoids and corals on surface; rocks at top dipping 60º, possibly by fault action; Permian material at base
2	5m	variable, 50–75º	no fossils eviden
3	2m	70º SW	pink limestone with abunant corals
4	2m	60º SW	abundant corals, possible fault in corner between Face 3 and Face 4
5	unknown	60º SW	no fossils; well-faulted, rubbly surface; well weathered
6	unknown	60–70º SW	no fossils

** Measurement perpendicular to the bedding plane, i.e. directly upwards through the strata.*

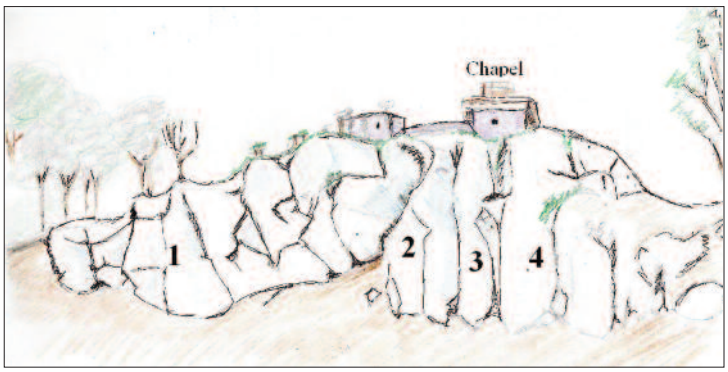

Figure 4 Sketch of the northern quarry faces, northernmost to the far left. Beds 5 and 6 continue to the south — for explanation see Table 1 (Richard Blagden).

In general we found most bedding surfaces dipping at 60–70º to the south-west, which was a close approximation to the RIGS citation (English Riviera Geopark 2015b). However, at least two faces were clearly dipping south and some of the higher parts, inaccessible to us, appeared to abut the SW-dipping faces. Quarrying has removed much of the crucial evidence, but we suspect that more than one phase of deformation took place, as in places the S-dipping beds appeared to overprint the SW-dipping beds (Figs 3 and 4).

At first glance the limestone appeared to be dull, grey and featureless, but judicious hammering revealed more details. Face 3 in particular was a striking pink colour and Figure 5 *(opposite)* shows a rugose coral extracted from Bed 1.

One interesting feature was the appearance of a reddish conglomerate material at the base of Face 1, and this is discussed at length in the description of the Sticklepath Fault, below.

The ruin of a limekiln can be seen just between the northern and southern quarries, and it would be interesting to research the story of the industry at Chapel Hill, with the railway station in such close proximity.

Figure 3 View of the northern quarries.

Permian Conglomerate

The exposure of Permian Strata at Chapel Hill Woods is located in a road cut by the side of Newton Road, which marks the western boundary of the site. The length of this exposure is c. 200m.

The general nature of the lithology of these rocks is a series of conglomerates or breccias dipping at *c*. 9º in a direction apparently towards the north-west, although this may not represent the true dip (Fig. 6). The breccias are interbedded with lenses of finer material, most commonly of fine to medium sand. The thickness of beds shows considerable variation from 100mm to 0.5m and, in places, poorly defined, graded bedding is visible — fining upwards. The majority of clasts in the breccias consist of Devonian limestones (up to 200mm in diameter), which contain frequent fossil fragments, including corals and brachiopods. Other, less common, clasts include quartz and very dark coloured, often black, fine-grained crystalline volcanics. The matrix of the breccias varies from silt to fine sand. The sand grains examined by hand lens were mostly angular and glassy. This lithology would be consistent with deposition in an alluvial fan environment.

The original aim had been to construct a generalised graphic log from the base of the exposure (at its southern end) to the younger units (at the northern end) by tracing the topmost beds in one location and following them to where they 'disappear' into the pavement, from which point the log could be continued upwards. However, this proved impractical, as many 'beds' are laterally discontinuous lenses. Therefore, only three sections are described here in more detail.

Section 1 The oldest exposure is located at the southern end of the road-cut, and the following description is of a section located close to the lower road direction sign *c*. 30m from the southernmost end of the exposure. The lowest unit in this section comprises c. 1.1m of matrix-supported breccia with clasts up to 200mm in diameter. The clasts are evenly distributed throughout the unit and the matrix is predominantly of silt size. As throughout the exposure, the clasts are predominantly of Devonian limestones with some quartz and dark volcanic rocks. Above this layer is a unit of variable thickness (typically *c*. 0.5m), with a coarser matrix (fine- to medium-grained angular sand) and more flattened clasts, including some red shales and mudstones, which are possibly re-worked local Permian sediments. Although more detailed analysis is required, there is a visual impression that these flattened clasts show signs of imbrication, indicating a palaeocurrent direction towards the north-west, in a similar direction to the dip. This layer possibly represents a small temporary channel on the surface of a larger alluvial fan. Above this unit is a variable thickness (0.8–2.1m) of the bedded breccias described in the second paragraph of Permian Conglomerate *(above)*, which form the dominant lithology of the whole exposure.

Figure 6 Roadside cutting of the Permian rocks

Figure 5 Rugose coral, from limestone Face 1 at Chapel Hill.

Section 2 is approximately in the centre of the exposure and is shown in Figure 5. It is dominated by beds of varying thickness of breccia (200–400mm), in which the number and size of clasts show a tendency to decrease from the base upwards. This may be consistent with deposition by flash-flood events; and *c*. 1.5m from the base of this section (the base being the pavement) is a bed with fewer clasts that show more obvious signs of imbrication than elsewhere on the exposure. The palaeocurrent direction indicated here is 'into' the face, or towards the north-east, which is possible evidence for variations in current directions consistent with shifting channels on the surface of a fan.

Section 3 The final section chosen for more detailed examination is located *c.* 30m from the 'top' (northernmost end) of the exposure, close to another direction sign by the side of Newton Road (Fig. 7). This site was examined because it may show a section through a large palaeochannel eroded into layered breccias. Apart from the possible channel margins marked by abrupt lateral changes in lithology, the units within the 'channel' are also more varied, containing lenses of reworked red shale and mudstone clasts set in a fine, silty matrix. These are visible as darker areas in Figures 7 and 8 *(overleaf)*.

The Sticklepath Fault

The most intriguing structural discovery on the site was at the base of limestone quarry Face 1. Here, adjoining the base of the limestone, we discovered a very small amount of red sandstone with rock fragments, similar to the Permian deposits at the bottom of the hill. This provoked considerable discussion and two theories were raised to account for its appearance.

It is not in dispute that the Sticklepath Fault runs along the western edge of the site, and that it was responsible for bringing the Permian rocks into contact with the

Figure 7 Section at northern end of exposure showing what may be a paleochannel.

Figure 8 Typical cross-section of a Permian rock.

Devonian Limestone (Fig. 9). However, the actual contact between the two is hidden by the extensive slope of talus, soil and quarried waste that forms the hillside. By definition, any point at which the Permian comes into contact with the Devonian here lies on the fault, and it was suggested that the deposit at the base of Face 1 must therefore be a very small part of the Sticklepath Fault. This would require the fault to dip *c*. 30-45°, but we have not been able to establish whether this is reasonable.

There were, however, issues with this argument. Limestone must surely have been quarried away from 'in front' of the deposit, so it is unlikely that this material abutted the leading edge of the limestone. The deposit did not appear in distinct strata as it did at the bottom of the site, so was probably not formed by the same actions — although it may have been reworked by fault movements. It was considered more likely that this material dropped or was squeezed up into a crack, either during the Permian or more recently, and does not therefore mark the line of the fault.

Figure 9 Chapel Hill seen from the southern approach along Newton Road. St. Michael's Chapel itself can be seen on the skyline top right, and the Sticklepath Fault runs through the valley on the far left.

Due to the small size of the deposit and the lack of corroborating evidence we were unable to adequately answer this question, but it would make an interesting focus for future research.

Summary

Chapel Hill is an interesting geological site showing good exposures of Devonian limestone and Permian breccias. It is an urban site with good transport links and can easily be explored from Torquay.

The underlying geology of the area is revealed very nicely from the chapel itself, with the limestone plateau of Torquay particularly prominent.

The Permian rocks exposed in the road cutting and the quarried Devonian limestone cliffs are each worthy of exploration in their own right and may reveal features not described here. The Sticklepath Fault runs through, or adjacent to, the site. It was not clear on our visit whether or not the boundary itself is exposed (*see* The Sticklepath Fault), but the relative positions of the rocks at least suggest that an unconformity is present, if not the fault itself.

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William Smith's last resting place

A joint OUGS and Geological Society visit to St. Peter's Church, Northampton, followed by a tour of All Saints Church, Brixworth (6 September 2015)

Ian Clarke

Introduction

As one of the events marking the 200th anniversary of the publication of William Smith's 1815 Geological Map, it was appropriate that a group of geologists should visit his grave and memorial at St. Peter's Church in Northampton. This idea was suggested to me at the OUGS 40th Anniversary Symposium in 2012, held in Northampton, by Dave Williams, one of the OUGS speakers. Dave mentioned that he was on a Geological Society committee planning events for the anniversary year, and that he thought something should be organised for Northampton. He suggested that as I live near Northampton perhaps I could make the arrangements, hence my involvement..

So on September 6, 2015, a group of 10 of us made up of Geological Society and OUGS members, assembled outside the Ibis Hotel, Marefair, Northampton, to meet Dr Diana Sutherland, our guide for the day. Diana is the author of *Northamptonshire Stone* (2003) and an expert on Northamptonshire geology.

Hazelrigg House, 33 Marefair

Our first stop was just across the road from the Ibis, at Hazelrigg House (Fig. 1), which is where William Smith died in 1839. What was Smith doing in Northamptonshire? According to Rev. R. M. Serjeantson in his *History of the Church of St. Peter* (1904):

> In August 1839, he [Smith] was specially invited to attend the meeting of the British Association in Birmingham. On his way he stayed with his friend, Mr G. Baker, the antiquary, and with him made several excursions into the neighbouring country. On one of these expeditions he contracted a chill, which led to serious complications, and in a few days put an end to his life. He died on August 28th. At the suggestion of Dr Buckland, a tablet and bust was erected at St. Peter's, the cost having been defrayed by a subscription amongst geologists.

It is not known how long Smith had been friends with George Baker and his sister Anne, or how often he came to Northampton. His county map of Northamptonshire is unfinished, so perhaps he was working on this as part of his visit.

Hazelrigg House is a Tudor town house, dating from 1570–1580, which is built of dark brown sandstone and ironstone from the Northampton Sand Formation. The doorcase is Cotswold (Taynton?) Limestone. There is a local tradition that Cromwell stayed at the house on his way to Naseby (1645). The house survived the Great Fire of Northampton in 1675. The Bakers, who bought the house in 1831, wrote a large, two-volume history of Northamptonshire.

Figure 1 Hazelrigg House, Marefair, Northampton.

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As well as looking at the front of the house, later in the morning we were able to peer into the rooms at the rear of the building. This was much to the consternation of the Through the Looking Glass Theatre Company, whose members were rehearsing inside. So much so that one of their leaders came out to see what we were up to. We explained who we were and gave him an information sheet about William Smith. He was very pleased with this, as the theatre group want to perform works that bring the history of the building to life. So perhaps William Smith's dramatic story will inspire a play (but hopefully not William Smith — the musical!).

St. Peter's Church

Just a short way from Hazelrigg House is St. Peter's Church, described in the recent new edition of Pevsner's *Northamptonshire* (Bailey *et al.* 2013) as "The most interesting Norman church in Northamptonshire and indeed one of the most exceptional Norman churches in the country".

Diana led us to William Smith's grave in the churchyard (Fig. 2). Here she read out the details of his death certificate and the obituary notice from the local newspaper, the *Northampton Mercury*. John Phillips, Smith's nephew, had arrived before Smith died and was present at the funeral. The gravestone is made of very weathered sandstone (New Red Sandstone, not local, source unknown) and the inscription of William Smith's name is now barely legible.

St. Peter's dates from AD 1160 and occupies the site of an earlier Saxon church. It is built of local brown sandstone and ironstone of the Northampton Sand Formation, with decorative features of Blisworth Limestone, giving a typical Northamptonshire polychrome effect. Inside the church, there is a memorial bust of William Smith (Fig. 3), by Matthew Noble. The inscription on the marble plinth reads:

> To honour the name of William Smith, LL.D. This monument is erected by Friends and Fellow-labourers in the same field of British Geology. Born 23rd March, 1769, at Churchill in Oxfordshire, and trained to the Profession of a Civil Engineer and Mineral Surveyor. He began, in 1791, to survey collieries and plan canals in the vicinity of Bath, and having observed that several strata of that district were characterised by peculiar groups of organic remains he adopted this fact as a principle of comparison, and was by it enabled to identify the strata in distant parts of this island, to construct sections, and to complete and publish in 1815 a Geological Map of England and Wales. By thus devoting, during his whole life, all the power of an observing mind to the advancement of one branch of Science, he gained the title of the "Father of English Geology".

Figure 2 William Smith's grave, St. Peter's Church cemetery, Marefair

TO HONOUR THE NAME OF
WILLIAM SMITH, L.L.D.
THIS MONUMENT IS ERECTED BY HIS FRIENDS
AND FELLOW LABOURERS IN THE FIELD OF
BRITISH GEOLOGY.

Figure 3 William Smith memorial in St. Peter's Church

Inside the church, Diana spoke about the building's architectural history, including the many Norman alterations and its partial rebuilding by George Gilbert Scott in 1850, the building stones and stone carvings — in particular a magnificent Anglo-Saxon tomb-slab decorated with a Green Man and fantastic birds and beasts. This tomb dates from the 10th or 11th century and is reputed to be the grave slab of St. Ragener, a little-known Anglo-Saxon prince, soldier and martyr (Sargant, accessed 29-12-2015).

All Saints' Church, Brixworth

After lunch, we continued to explore the Saxon theme by visiting All Saints' Church, Brixworth, a few miles north of Northampton (Fig. 4, *opposite*). All Saints' is one of the most outstanding examples of Anglo-Saxon architecture in England. It dates from the 8th and 9th centuries. Diana has spent many years working on identifying the many building stones used in its construction, especially in the Saxon parts of the church, and tracing the history of the building's development. We began our tour inside the church and she told us about the main points in the building's history: Saxon, later medieval and especially the 19th century restoration by Rev. C. F. Watkins. Watkins did a wonderful job in restoring Anglo-Saxon features, rebuilding the polygonal apse and revealing the ambulatory that had been covered by medieval stonework. The ambulatory, a walkway for pilgrims, is a semi-circular, sunken, outer ring-crypt surrounding the apse. A highlight of the tour was to be able to go up into the stair turret and see the use of tufa in the construction of the turret's stair vault.

Figure 4 All Saints' Church, Brixworth.

Outside, Diana treated us to a geological feast, as we examined some of the building stones around a small door on the south side of the tower (Fig. 5). These include bedded tuffs, diorite, Markfieldite, granite, mica hornfels, Swithland Slate, grey and red Triassic sandstones, and many Roman bricks (Fig. 6). None of these stones is local, all originating in Leicestershire, and they are thought to have been reclaimed from Roman buildings in Leicester (Roman name Ratae) and brought about 35km to Brixworth for use in building this very prestigious church.

However, as well as these imported igneous rocks and sandstones, there is plenty of Northamptonshire stone. This includes eight types of Northampton Sand, Blisworth Limestone and tufa. Northampton Sand was quarried locally, but the Blisworth Limestone may come from Towcester, 25km away. The tufa could have been found locally, but, like much of the church's stone, could have come from a Roman site.

This was a fascinating day of geology, history and architectural delights. Thank are due to Diana Sutherland for showing us such wonderful buildings and explaining everything so well; and to The Churches Conservation Trust for allowing us access to St. Peter's and to the Friends of All Saints' Church, Brixworth, who enabled us to go up into the stair turret.

Further reading

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Figure 5 Dr Diana Sutherland showing the mixture of building stones at the small door, All Saints' Church.and Brixworth.

Figure 6 Brixworth Church's patchwork of building stone and arch of Northampton Sand.

Book review

Floyd, Peter A. 2015 *Building Stones and Stone Buildings of Staffordshire*. Ilfracombe: Arthur H. Stockwell Ltd (ISBN 978-0-72234-543-6; paperback ; £14.95)

This book, written by Dr Peter Floyd (a Reader in Geochemistry at the University of Keele until his retirement), focuses on building stone obtained from Staffordshire and buildings in the county that utilise this. The author tells us in his Preface that the book is aimed at people who are interested in natural history and earth science, rather than professionals, but he also expects it to be useful to a very specific group: people involved in stone building restoration.

The book is divided into three parts, each part having a narrower focus than the preceding one. The scope of the first part of the book is very wide. It begins with a brief overview of stone building in Staffordshire from the Stone Age to the present and an overview of studies and databases of local building stone. We are then introduced to igneous, metamorphic and sedimentary rock types, to geological time and to the geology of the UK, with particular reference to the origin and some of the geological processes associated with various types of rocks used as building stone. Next there is a section on conservation and restoration, which includes an overview of physical, chemical and biological weathering processes as they affect building stone. The author then goes on to discuss restoration and the problems of sourcing suitable stone with properties that are as close as possible to the original. This is followed by a very brief introduction to architectural styles, with guidance to the reader on how to find out more. Next there is a short section on masonry, which is helpful in showing how building stone may be oriented and dressed; and finally there is a section on the terminology of architectural features found in churches, castles and country houses.

Thus the first part of the book gives us condensed introductions to various topics, supported by many references to printed material and websites so that the reader can readily explore any of these topics in greater detail. Part 1, like the rest of the book, is copiously illustrated by photographs and diagrams, although some images would have benefited from improved resolution.

The second part of the book discusses the geology of Staffordshire: the majority of the county has Triassic bedrock, with some significant areas of Carboniferous rock and smaller areas from the Permian and Silurian. The author provides a simplified geological map of the county and a comparison of active quarry sites in 1851 and 1994. He then outlines Carboniferous, Permian and Triassic geological processes and the stratigraphy of the area. Those who have walked around Staffordshire will be pleased to learn the origin of the rounded, liver-coloured pebbles found in several of the formations of the Sherwood Sandstone Group: these quartzite pebbles were eroded from the Variscan uplands of Brittany, and were carried northward by a large, braided river system. Next the author turns his attention to the problem of identifying rock used as building stone, and in particular the problem of distinguishing between building stones that look superficially similar. In Staffordshire, sandstone is used widely as a building stone, but there are many different sandstone formations; and for those involved in restoration it is critically important to identify the original stone and to locate the source quarry. Emphasising that visual inspection is often not sufficient for definitive identification, the author outlines the differences that can be observed by visual inspection in the field, the differences that can be seen in thin section, and the geochemical differences between different formations, using a combination of textual explanation, tables, graphs, and photographs.

The third and longest part of the book (nearly 200 pages) is devoted to individual descriptions of stone buildings in Staffordshire. As the author notes in the Preface, this was one of the main aims of the book. This part deals in turn with fortifications, churches, halls and country houses, and vernacular buildings. Each section begins with an overview followed by an account of individual buildings, detailing location, historical aspects, architectural features, and building stone, together with images, which typically include an overall view of each building and a close-up view of its building stone. There are also a few historical images and some close-ups of architectural features. Altogether the author identifies and describes more than 100 individual stone buildings, and he is able within his scheme of description to incorporate interesting snippets of non-geological information such as archaeological finds, information about the owners, or architectural decorations. This part of the book is more accessible, using less technical language than Parts 1 and 2, making this a good starting point for non-specialist readers.

The different parts of the book are suited to different audiences. For example, sections from Part 2 would be particularly relevant to readers who might be involved in stone building restoration, or students who are interested in finding out about the geochemistry of local sandstone, while Part 3 is more accessible to a general audience. Most readers are unlikely to read the book sequentially — they are more likely to pick out areas of interest. To address the different needs of these varied audiences I would have liked to see the addition of a glossary, and full referencing of the websites, which are provided in the Reference section simply as a list of website addresses.

Overall, this is a unique resource, gathering together a wide range of information relating to the building stones, stone buildings and geology of Staffordshire.

— Sandra Morgan, OUGS West Midlands Branch Organiser

Exploring the Afon Cleddau Valley in Pembrokeshire: a geological itinerary

John Downes

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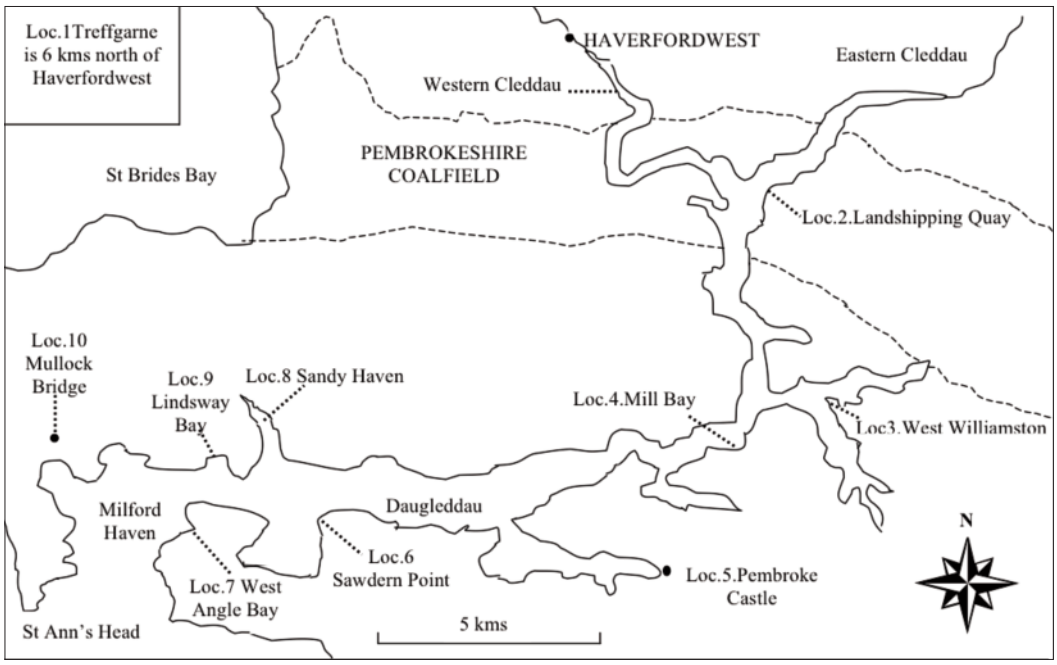
Introduction

The Afon Cleddau has two main headwaters, the western and the eastern branches, which have their confluence at Picton Point; south of this locality the main river is known as the Daugleddau (Fig. 1). North of Haverfordwest, the Western Cleddau flows through the spectacular Treffgarne Gorge, which represents a glacial overflow channel, and the nearby rhyolitic crags of Maiden Castle rise above the western side of the gorge. The main river neatly bisects the Pembrokeshire Coalfield and in the 19th century it provided a natural outlet for local anthracite required for iron making and lime burning. Hook on the Western Cleddau and Landshipping Quay on the Daugleddau were busy river ports exporting coal at that time.

The southern margin of the coalfield is marked by a linear outcrop of Carboniferous Limestone, which has been quarried extensively for building stone and more recently for limestone aggregate. The quarries at West Williamston on the Carew River were worked in the 19th century and the stone was transported downstream on sailing barges. Pembroke Castle and many of the numerous forts and defensive works that line the Lower Haven were built from locally quarried Carboniferous Limestone. The whitewashed tower of Benton Castle is a conspicuous landmark rising above the woods on the western side of the Daugleddau. Geologically this building is significant in that it gives its name to the Benton Castle Fault, a major thrust produced by the Caledonian Orogeny and later reactivated during the Variscan earth movements.

The river gets significantly wider below the Cleddau Bridge and the presence of docking facilities, oil refineries and oil terminals (jetties) makes considerable impact on the natural environment. Despite these industrial developments along the Lower Haven, there are numerous small, unspoilt bays, including Sandy Haven, Lindsway Bay and Dale Roads, where interesting geological localities can be accessed.

Figure 1 The Cleddau Valley and surrounding area.



The Cleddau is a classic example of a drowned river valley or ria produced by the late Flandrian rise in sea level less than 10,000 years ago. The branching pattern of drowned tributary streams provides an ideal environment for mooring small fishing and pleasure boats. These tributary valleys are locally known as pills (e.g. Cosheston Pill, Sandyhaven Pill), the sides of which are often wooded while the silted headwaters are colonised by salt marsh, providing a haven for wild life.

Localities to visit

Starting in the upper reaches of the Western Cleddau, the itinerary follows the river downstream to its estuary as it crosses a sequence of geological outcrops.

1. Maiden Castle [SM 955248] and the Treffgarne Gorge [SM 958250]

The crags of Maiden Castle and neighbouring Poll Carn form prominent outcrops of the Roch rhyolite on the west side of the Treffgarne gorge (Fig. 2, *overleaf*). This locality is *c*. 9km north of Haverfordwest on the A40 Fishguard road. Park in the lay-by at Nant-y-Coy Mill where there is an excellent tearoom and craft shop. Walk up the narrow lane on the south side of the mill and after *c*. 100m take the footpath that leads to Maiden Castle and beyond to Poll Carn. These rugged tors are formed of flow-banded rhyolitic lavas that are also nodular and brecciated in places (Fig. 3, *overleaf*). The viscous, silica-rich lava flow would have had a congealed crust, which was broken up and fragmented by the continued movement of the molten lava underneath the crust. This autobrecciated lava can be recognised in the outcrop by its fractured appearance that is recrystallised on some surfaces. The rocks at this locality belong to the Roch Volcanic Formation that extends south-westwards *c*. 8km in a prominent line through Plumstone Rocks and Cuffern Mountain to Roch Castle [SM 880211]. Although these Roch Volcanics have long been considered to be of Precambrian age, the BGS now assign them to the Arenig Series of the Ordovician.

Maiden Castle and Poll Carn are important geomorphological sites for the study of the formation of tors. The physical appearance of the tors can be described as upstanding irregular masses of rhyolitic lavas surrounded by blockfield slopes (Fig. 4, *overleaf*). The large blocks that litter the slopes have clearly been detached from the main outcrop. Many researchers consider that the tors evolved under periglacial conditions during the late Devensian, when the area is thought to have been just beyond the maximum ice limit. On the

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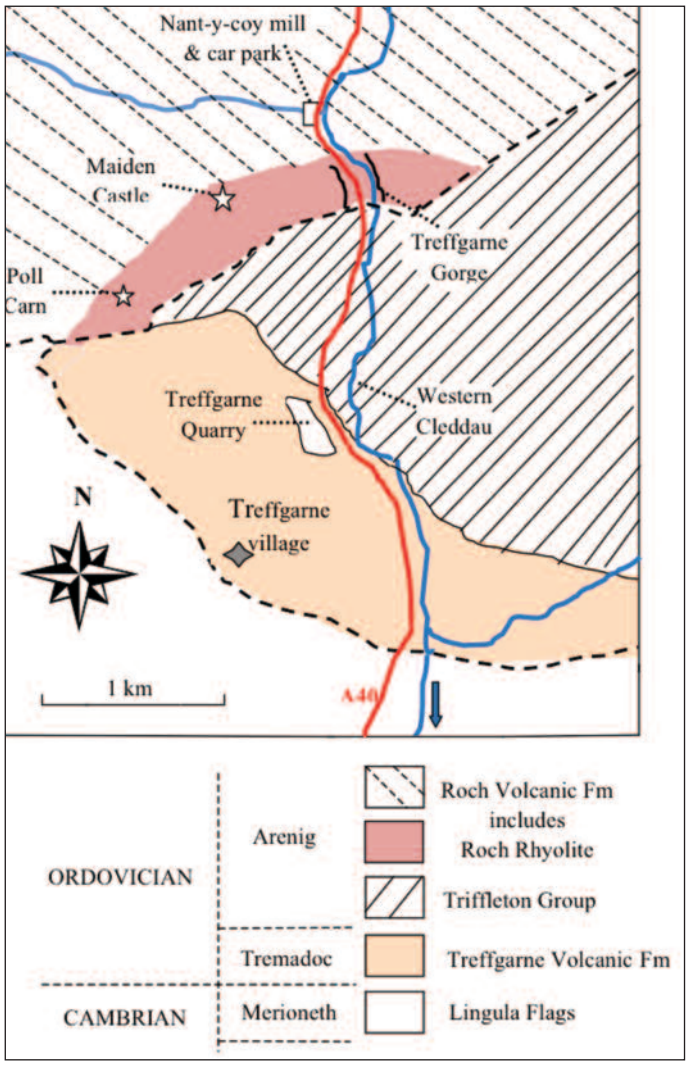


Figure 2 The geology of the area around Treffgarne.

other hand, Linton (1955) proposed that the Preseli tors were formed by a two-stage process, involving deep tropical weathering during the Palaeogene followed by mass wasting under periglacial conditions during the Pleistocene.

Just to the east of Maiden Castle, the outcrop of the Roch Volcanics crosses the Western Cleddau valley where the Treffgarne Gorge has been cut through the resistant rhyolite. This spectacular gorge represents a glacial overflow channel formed when subglacial meltwater escaped from beneath the ice sheets that were marginal to the Preseli uplands in late Devensian times. The Scleddau overflow near the head of the Western Cleddau would have carried meltwater southwards, and this would have been impeded by the rock barrier at Treffgarne, but which overflowed through the gorge.

The Treffgarne Volcanic Formation of Lower Ordovician age (Arenig Series) is exposed in a large disused quarry [SM 959240] on the west side of the A40 road immediately north of the village of Treffgarne. The quarry is now flooded and the sides are rather overgrown. However, it is possible to scramble around to the western face of the quarry where there are ripple marked ashes, and mud cracks have been recorded in the past suggesting that the ashes were deposited under water, either in a marine or

Figure 3 Maiden Castle: Ordovician rhyolitic tors.

crater lake environment. On the northern side of the quarry there are andesitic tuffs and agglomerates. The latter may be autobrecciated as a result of the breaking up of the congealed crust of a lava flow. Some of the lava contains pods of pyroclastic material (lapilli up to 5mm in diameter) and volcanic bombs 'some several feet across' were noted by Professor T. R. Owen (1971). The Treffgarne Volcanic Group is more than 150m thick and dips steeply to the north. It rests unconformably on the Lingula Flags of Upper Cambrian age. The volcanics are succeeded by the Triffleton Group, a sequence of interbedded siltstones and sandstones, which are poorly exposed in the nearby Triffleton Quarry [SM 977243].

2. Landshipping Quay [SN 008108]

From Treffgarne follow the A40 to Haverfordwest and continue eastward to Canaston Bridge. Then take the A4075 to Cross Hands [SN 072120]; turn right and drive along the minor road to Landshipping Quay on the Eastern Cleddau. This was one of the most important 19th-century coal exporting ports on Afon Cleddau. The remains of the stone quay can be seen on the south side of Landshipping Pill, a small inlet *c*. 1.5km beyond Landshipping village. There is a small car park on the bridge near

Figure 4 Maiden Castle viewed from the west.

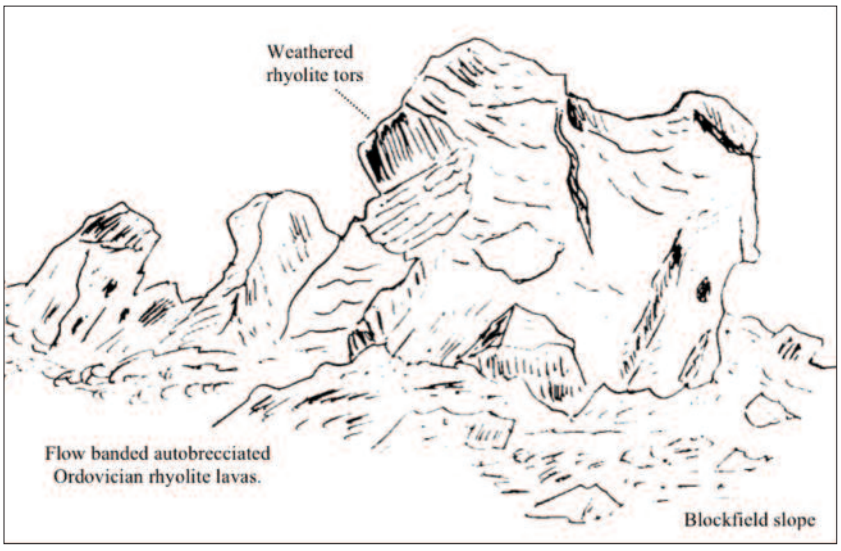
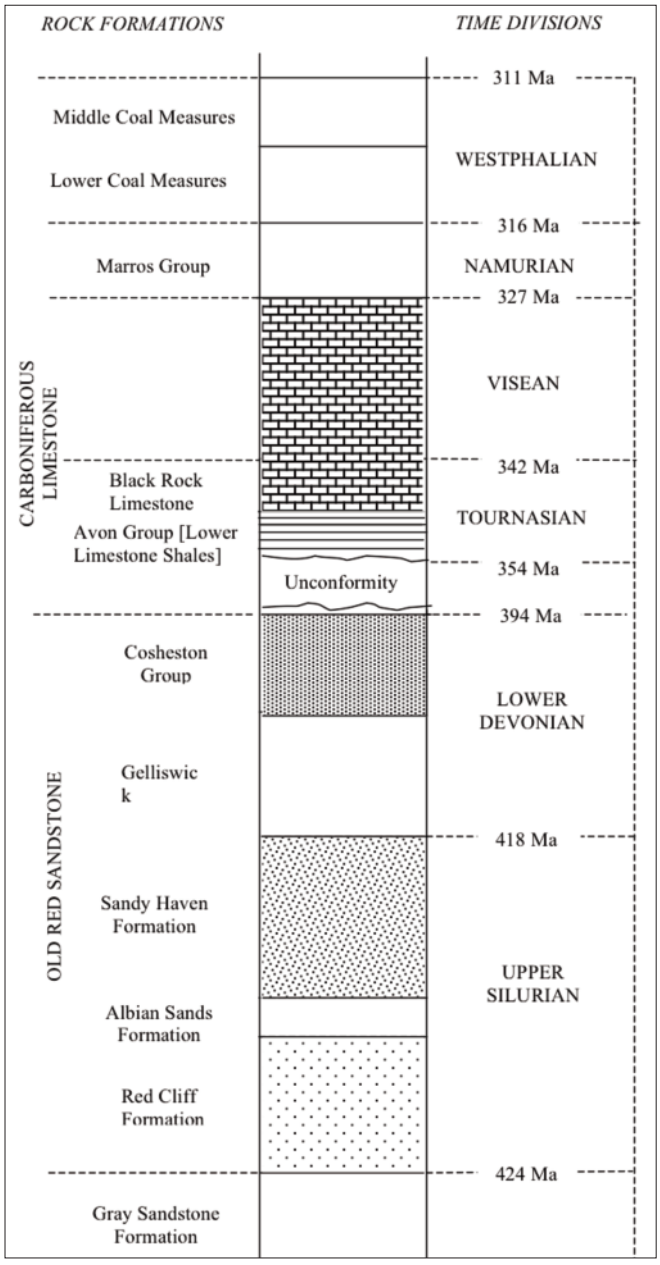


Figure 5 Memorial to the miners killed in the Garden Pit disaster of 1844.

Figure 6 Stratigraphical Column for the Cleddau Valley south of Haverfordwest.



the quay and near by is a memorial at to the 40 miners who lost their lives in the infamous Garden Pit disaster in 1844 when mine workings were flooded by river water (Fig. 5).

At low tide, walk along the foreshore below the low river cliffs on the north side of the pill, where you will see the Middle Coal Measures exposed (Fig. 6). Thin coal seams and seat earths containing plant remains within the Timber Vein Group crop out at the western end of the section, but they are much contorted by Variscan folding and thrusting. There are examples of cross-cutting, sandstone-filled channels (Fig. 7), wedging-out structures and numerous bedded ironstone nodules. At the far end of the section there is a distinctive 2m-thick bed of orange coloured ironstone concretions. A large shallow anti-cline on the foreshore shows rectilinear jointing, ripple bedding and evidence of polygonal mudcracks.

Figure 7 Sandstone-filled channel cross-cutting shales in Middle Coal Measures.

About 300m south of the ruined quay, the foreshore exposes cyclothem units of the Lower Coal Measures dipping *c*. 50º SE. However, there is considerable evidence of northward propagating Variscan thrust movements in the folded strata. One example at SN 105005 shows a thrust fault where the upper half of a fold has been carried northward along the thrust plane. There are several folds showing spaced cleavage in the siltstones between the more competent sandstone layers. The fold axes generally trend NW–SE as in the synclinal structure outlined by sandstone ribs on the foreshore near to the southern end of the section. The foreshore rock exposures are cut off by a major E–W fault at SN 003101 and south of this point there are no further coal measure outcrops.

3. West Williamston Quarries [SN 025061]

From Landshipping return to the A4075 and drive to the junction at SN 057054, just south of Cresselly; turn right along the lane to West Williamston. The disused Point Quarries can be accessed by a footpath from the west side of the village. The quarries were major producers of limestone in the early 19th century when their tidewater location enabled the stone to be transported around the Welsh coast. Barges of 15–20 tons were loaded in the tidal channels that joined the quarries to the river (Fig. 8, *overleaf*), and then moved to Lawrenny quay to be transhipped on to coastal vessels. The limestone was in great demand at the time for use in

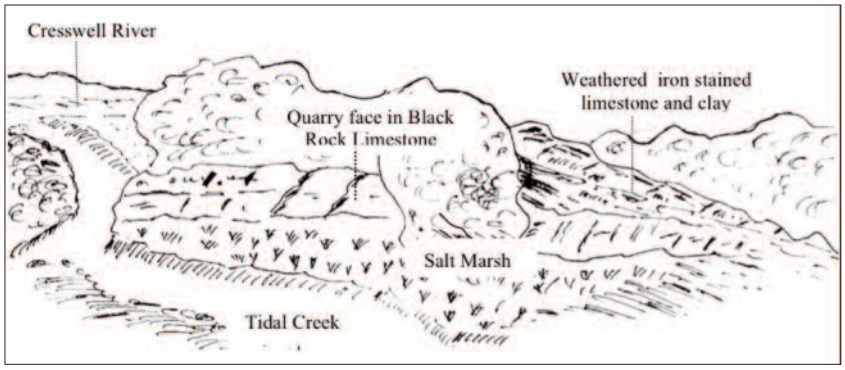
Figure 8 Tidal channels formerly used by barges entering Point Quarry.

limekilns to produce agricultural lime, mortar and whitewash for houses. Records show that in 1839, a 40-ton sloop called *Ranger* carried 10 cargoes of limestone from Lawrenny to Abercastle on the north coast of Pembrokeshire. At the time of the Napoleonic wars there was a great demand for stone to build the complex of fortifications to protect the Milford Haven. West Williamston quarries were ideally located to supply limestone blocks for transport by barge direct to the forts. Many of the Admiralty buildings in Pembroke Dock were also constructed of limestone from these quarries.

You can get to the old quarries from the A4075 road at Carew by following the narrow lane past Carew mill pond to West Williamston. There is a small car park at SN 033059. Follow the driveway to Williamston Park, from where a public footpath leads down to the salt marsh alongside the Carew River. The site is on a promontory at the confluence of the Carew and Cresswell rivers. About 200m before reaching the north-west end of the site, there is a footpath leading through the trees to Point Quarry where the limestone is exposed (Fig. 9). Today the quarries are largely overgrown, but they provide a haven for wildlife and natural vegetation protected as a designated SSSI and managed by the Wildlife Trust of South and West Wales.

The Lower Carboniferous succession at West Williamston is *c*. 300m thick and the strata lie on the flank of the Carew Anticline, dipping *c*. 25° NE. The fine-grained grey oolite at Point Quarry belongs to the Black Rock Limestone and its homogeneous texture make it an excellent building stone. On the top of the ridges between the tidal creeks there are several metres of 'rotten beds' that are deeply weathered. This is a palaeokarst horizon where the limestone is pitted by chemical weathering and some faces show solution hollows up to 300mm in diameter. There are also numerous infilled fissures. The reddish clay infill appears to represent a weathering residue of insoluble clay minerals in which there are rounded fragments of unweathered limestone. The deeply weathered beds were probably formed as ground water percolated through bedding planes and joints resulting in solution of the limestone at depth. During Lower Carboniferous times, the hot, wet tropical conditions would have been ideal for the development of these palaeokarst features.

Figure 9 Point Quarry at West Williamston.



4. Mill Bay [SN 002049]

From West Williamston return to the A4075 and drive south to the A477; turn right through Milton and continue on the main road towards Pembroke Dock. Turn left into Cosheston; at the village crossroads continue northward *c*. 1km to Rosehill Cottage. On the west side of the road there is a wooden gate that gives access to a track leading down through a wooded valley to Mill Bay. This is a permissive path that is closed to the public during December and January. It is best to approach Mill Bay at low tide in order to gain access to the rocks in safety.

Figure 10 Ball-and-pillow structures in the Cosheston beds (Lower ORS) in Mill Bay.

The most interesting geological aspects of this locality are the soft sediment deformation structures in the Cosheston Group of the Lower Old Red Sandstone. On reaching the river take the path to the left and walk *c*. 300m to where a set of steps leads down to the rocky foreshore at SN 999050. Look carefully at the low cliff face and you will see classic ball-and-pillow structures below the base of a sandstone bed. This occurs where rounded masses of sandstone have sunk into the underlying mudstone when it was still soft and unconsolidated (Fig. 10). It has also been argued that seismic shocks may convert overlying sediments into quicksand that then founders into the mud. There are examples of soft sediment deformation on the rock foreshore where sandstone pillows are enclosed in slumped sediment. About 200m to the west there is a beautiful example of an anticlinal fold that has been cut by a reverse fault, while the whole structure is underlain by slumped mudstones.

Return to Mill Cwm and cross the stream to the east side of Mill Bay to examine the founder folds (slump folds) on the foreshore at SN 003050. It is important to recognise that these folds are not produced directly by earth movements, but rather by the gravity-induced collapse of overlying wet sediment that slumped down a depositional slope. Walk farther to the east of the folds and look for river channels that cross-cut the bedded strata. You should see where a curved erosion surface is overlain by channel-fill deposits.

Finally, it is worth considering what these sedimentary structures at Mill Bay can tell us about the environment of deposition when the beds of the Cosheston Group were deposited. It is generally considered that by early Devonian times braided, meandering rivers crossed the floor of a large east–west graben (rift valley) bounded by the Benton and Ritec faults. These rivers laid down repeated fining-up cycles of conglomerate, sandstone and mudstone. Shifting of distributaries during floods would result in the sediments being cross-cut by new channels.

5. Pembroke Castle [SM 982016]

Many tourists come to Pembroke to visit the Norman castle (Fig. 11), which dates from the early 12th century when Robert de Montgomery first established a fortified settlement at the head of the tidal Pembroke River. However, it was not until c. 1200 that the first limestone walls and the round keep were built by William Marshall, Earl of Pembroke. In 1457 it became the birthplace of Henry Tudor, Earl of Richmond, who later became Henry Vll. The building was a Royalist stronghold during the English Civil War and it was partially destroyed in 1648 when Cromwell laid siege to it.

The castle is built on an outcrop of steeply bedded Carboniferous Limestone that is best seen in Westgate Street below the castle walls. Here we are standing approximately in the centre of the Pembroke syncline, which trends WNW–ESE. The youngest rocks preserved within the synclinal structure are equivalent in age to the Stackpole Limestone. A small outlier of gash breccia rests on the eroded limestone surface on Castle Hill, and if you look carefully you will see evidence of the reddish-coloured breccia in Westgate Street and also in Wogan Cavern under the north side of the castle. It is a pleasant walk around the mill pond where you can look over the sluice gates to the Pembroke River, alongside which are several old limestone quarries that were used to provide building stone for the town.

Figure 11 Pembroke Castle built of local Carboniferous limestone.

Figure 12 Calcretes developed normal to the bedding in red mudstones of the Ridgeway Conglomerate Formation near Sawdern Point.

6. Sawdern Point [SM 888032]

From Pembroke take the B4320 road to Angle. Turn right at SM 908004 along the minor road signposted to Rhoscrowther and then follow the private road along the coast towards the oil refinery. Sawdern Point is a low promontory on the east side of Angle Bay. The Ridgeway Conglomerate Formation (Lower Old Red Sandstone) is exposed in the low cliffs and on the foreshore around Sawdern Point. These rocks are the lateral equivalent of the Cosheston Formation on the north side of the Ritec Fault. They consist of a succession of thick conglomerate beds separated by cleaved red mudstones with calcretes at right angles to the bedding (Fig. 12). The extraformational conglomerates contain clasts of quartzite, felsite, phyllite and lithic sandstone held in a coarse sandy matrix (Fig. 13). The conglomerate units are poorly sorted and have sharp erosional bases. The formation thickens towards the Ritec Fault and according to Hillier and Williams (2007) it was probably deposited in a half graben by an alluvial fan that prograded northward towards the hanging wall of the fault. The Lower Palaeozoic provenance of the conglomerate clasts is considered to be in the Bristol Channel fault zone. The coarse-grained alluvial fan material interdigitates with fine heterolithic sandstones and mudstones laid down in low gradient, high sinuosity fluvial channels occupying the E–W axial zone at the foot of the Ritec Fault.

Figure 13 Ridgeway Conglomerate containing clasts of quartzite, felsite, phyllite and lithic sandstone.

The Skrinkle Sandstone Group (Upper Old Red Sandstone) is faulted against the Ridgeway Conglomerate Formation *c*. 400m ESE of Sawdern Point. Here mudstones, medium-grained sandstones and thin conglomeritic units are present on the downthrow side of the fault. An alternating sequence of red and grey mudstones and sandstones is well exposed on the foreshore around SM 897026, and the grey calcareous mudstones record evidence of an increasing marine influence, heralding the onset of the Lower Carboniferous marine transgression.

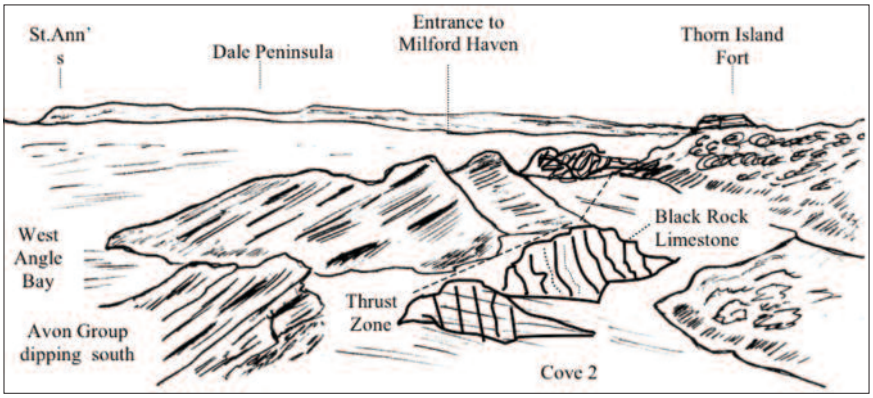


Figure 15 View across the north shore of West Angle Bay.

7. West Angle Bay [SM 855033]

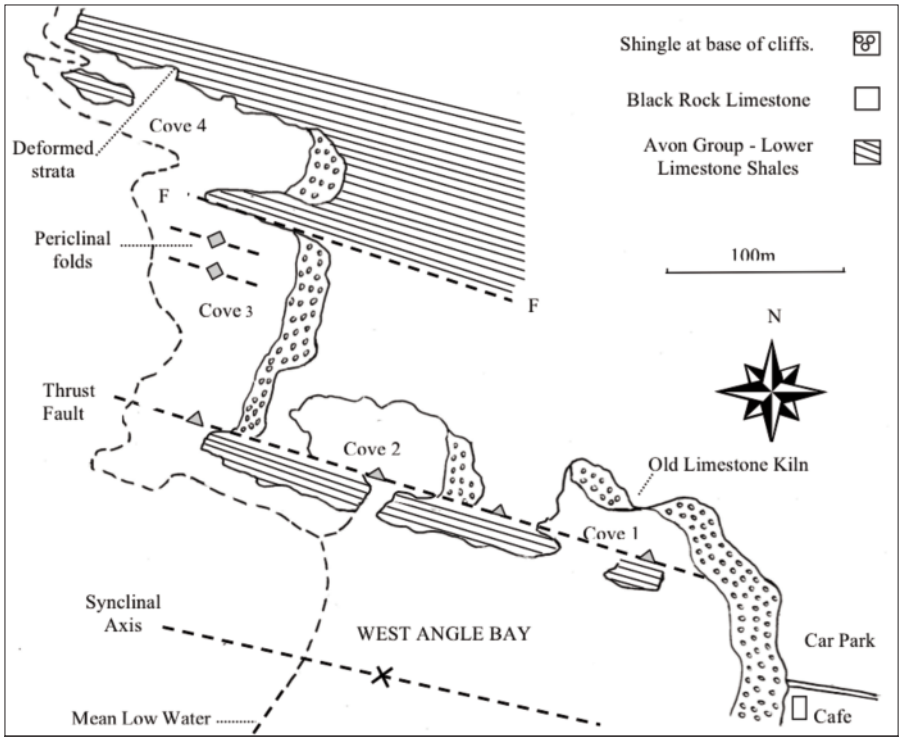
Return to the B4320 and follow this road through Angle village to the large car park adjacent to the beach in West Angle Bay. There is a café open during the tourist season and there are toilets next to the car park. The Hibernia pub in the village serves excellent refreshments.

At low tide, when the rocks are fully exposed, I suggest that you stand on the low sea wall near to the café and look out across the bay and the entrance to the Milford Haven. Large oil tankers and the new LNG vessels have to negotiate this relatively narrow stretch of water between West Angle and St. Ann's Head and it was here that the ill fated *Sea Empress* was grounded in 1996 with the loss of 72,000 tonnes of crude oil that polluted the coastline for miles around. This is part of the environmental price we have to pay for relying on imported oil and gas, but also from an aesthetic point of view, the existence of the three large oil refineries on the Haven is an ever-present blot on the landscape, especially in a National Park!

From your viewpoint you will also be able to observe the line of the synclinal axis that trends WNW–ESE on the south side of West Angle Bay (Fig. 14). You will see the dark grey limestones and shales of the Avon Group outcropping on either side of the bay, with the younger Black Rock Limestone occupying much of the area beneath the sandy beach. Now walk along the foreshore to the first cove that lies below a ruined limekiln on the north side of the bay. Here you should be able to see the Avon Group strata dipping towards the south and resting discordantly upon the almost vertical beds of Black Rock Limestone. Here there has been a strong thrust movement pushing the Avon Group rocks northward over Black Rock Limestone. The line of this thrust fault can be traced through Cove 2 and into the south side of Cove 3 where a narrow zone of brecciated limestone marks the lower side or footwall of the thrust (Fig. 15). These broken and shattered rocks are the result of movement along the thrust fault during the Variscan earth movements (Fig. 16).

Figure 16 Thrust plane between the Avon Group and the underlying vertically bedded Black Rock Limestone in West Angle Bay.

Figure 14 The geology of the northern shoreline of West Angle Bay.



Walk over the rocks into Cove 3, where you will see several other interesting geological structures on the foreshore, including two periclinal folds that appear as shallow elongated domes rather like the upturned hull of a boat. The axes of the folds are orientated parallel to the main synclinal axis of West Angle Bay. The rocks are also cut by a series of en échelon veins that are where the rock has been sheared and the resulting tension gashes have later been filled with the mineral calcite. You may also notice some small circular holes with radiating fractures *c*. 300mm long.

These are not natural features, rather they result from blasting operations during quarrying many years ago.

Some of the polished, light-grey limestone beds contain excellent examples of stylolites marked by an irregular suture-like contact that has been produced by pressure solution. This involves the removal of calcite grains in solution leaving a concentration of insoluble clay residues along the wavy stylolite surface. You will also find solitary corals such as *Zaphrentis*, crinoids and brachiopod shells preserved in the limestone. Some beds are much disturbed by burrows that cut across the bedding and are now infilled with slightly coarser sediment. These burrows are referred to as trace fossils since the original organism that produced them has long since been destroyed.

The northern wall of Cove 3 forms a faulted contact between the Black Rock Limestone and the deformed rocks of the Avon Group in Cove 4. You can get into this cove by scrambling through the gap in the steep dividing rock wall or alternatively it is possible to climb down the steep and narrow path that leads off the coastal track. It is well worth looking at the northern cliff face of the cove, where there are some well-developed Variscan deformation structures. The dip here is *c*. 70º SSW and a distinctive deformed sediment horizon occurs towards the western end of the cliff face at SM 851036.

Deformation features include a series of truncated minor folds and slump structures. These are found in the less resistant calcareous mudstone that is sandwiched between the harder limestone layers (Fig. 17). The mudstone in the crumple zone is also strongly cleaved at an angle to the bedding owing to the intense pressure exerted during earth movements.

Return to the car park in order to examine the Quaternary drift section that extends *c.* 100m south of the café. The low cliffs are strongly weathered so that downwash often obscures much of the stratification. Above the present storm beach there is a red sandy deposit containing pebbles from a raised beach that is now largely covered by shingle. Sub-rounded boulders up to 300mm across also occur in this layer. A distinctive orange unit with large sub-angular clasts forming the Blocky Head can be seen at the northern end of the section adjacent to the sea wall. This is succeeded by a sequence of sands, silts and dark grey clays containing shell fragments that may be related to a marine transgression. The dark clays have been washed down to beach level in the centre of the section. A red sand and pebble bed, c. 3m thick, occurs near the top of the cliff and this could be the product of fluvioglacial outwash from the Irish Sea ice sheet. A layer of sandy loam caps the drift deposits around much of West Angle Bay.

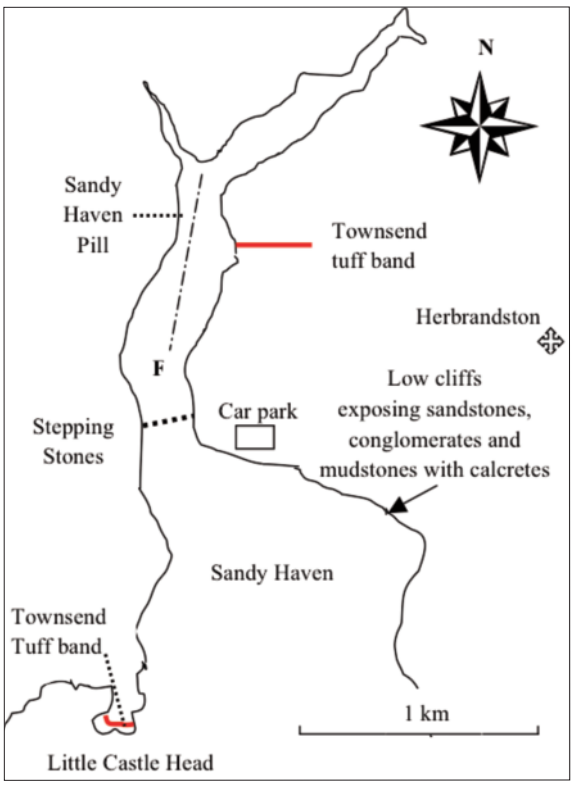
Figure 17 Defor-mation of calcareous mudstone between resistant bands of limestone in Cove 4 of West Angle Bay.

The most significant aspect of this section is the existence of a stiff, purple-coloured clay containing igneous erratics that was found in excavations made by E. E. L. Dixon of the Geological Survey in 1921 and by D. Q Bowen of Aberystwyth University in 1977. This till lies below the raised beach deposits and therefore must have been laid down by an earlier pre-Ipswichian glaciation. Thus West Angle Bay contains one of the longest sequences of Late Pleistocene deposition in south-west Wales, including glacial, interglacial and periglacial sediments ranging in age from c. 140,000 to 10,000 BP.

8. Sandy Haven [SM 856072]

To reach the north side of the Cleddau estuary from Pembroke, it is necessary to cross the Cleddau Bridge (Toll 75p for cars). Sandy Haven is *c.* 5ks west of Milford Haven. There is a small car park overlooking the foreshore at SM 856074 at the end of the lane leading down from Herbrandston. The geological section includes the foreshore on the east side of Sandy Haven and part of the east side of Sandy Haven Pill (Fig. 18). The middle division of the Sandy Haven Formation is exposed at low tide for *c*. 300m in Sandy Haven Pill, north of the bottom of Middlekilns Lane. All the strata dip *c*. 40º S along this section, which is mostly composed of a series of red mudstones rich in nodular calcretes, many of which have been dissolved out leaving a honeycomb structure. Two thick conglomerates containing exotic vein quartz pebble clasts are exposed *c*. 70m and 100m from the northern end of the section. However, the most significant feature

Figure 18 Sandy Haven.



is the abundance of air-fall tuffs of variegated colours, which were called the 'magenta beds' when Cantrill *et al*. of the Geological Survey first surveyed the area in 1916. Most of the tuff beds are a few centimetres thick, but the Townsend tuff, which crops out in the middle of the section, is almost 4m thick. This distinctive regional marker horizon extends across South West Wales and comprises three graded air-fall units, each fining upwards. The light-coloured porcellanite (silicified dust tuff) contrasts with the darker, magenta-coloured, medium-grained, crystal-lithic tuff at the base of each fall. Note that there is also an excellent section in the Townsend tuff at Little Castle Head on the west side of Sandy Haven (see *OUGS Journal* **35**, 26–7).

The foreshore and cliffs of Sandy Haven to the south of the car park provide a representative section through the upper part of the Sandy Haven Formation. At the western end of the foreshore near steps giving access to the beach, there is a distinctive grey conglomerate, steeply bedded and overlain by red mudstones. Farther east, the sequence is dominated by a 3m multi-storey unit of cross-stratified, medium-grained sandstones dipping *c.* 40º NE. These are overlain by thick mudstones festooned with calcretes and honeycombed where the calcareous material has been dissolved out. The mudstones are cleaved at a high angle to the bedding and the calcretes have been elongated along the cleavage planes. Near the eastern end of the foreshore the effect of Variscan deformation can be seen where interbedded mudstones and grey conglomerates have been tilted to a near vertical position.

The succession in Sandy Haven shows a series of fining-upward cycles, typical of deposition in a meandering river environment, where cross-stratified fine- to medium-grained sandstones represent point bar sediments and finer-grained mudstones represent alluvial flood plain deposits. Traditionally, these sediments have been considered as overbank deposits, but they are now thought to be laid down by ephemeral, sinuous streams that reworked the flood plain during seasonal flooding. Modern analogies for mudstone deposition within the Old Red Sandstone can be seen in the Channel Country of central Australia.

Coarse sandstones or conglomerates (lag gravels) rest on an erosion surface at the base of each cycle and the overlying mudstones are often calcretised and contain mud cracks. The calcretes in the mudstones are white, cylindrical or irregular-shaped masses that are several millimetres across and elongated normal to bedding and parallel to the cleavage. These masses are carbonate-rich, so they weather out easily. Calcretes represent fossil soils produced in a hot savannah climate of alternating dry and rainy seasons. In the wet seasons, ground water percolated down through the mudstone and picked up calcium carbonate and other minerals. In the dry seasons, the waters were drawn up by evaporation and deposited much of their mineral load, commonly replacing or filling rootlets or making irregular nodular masses within the soil.

9. Lindsway Bay [SM 843067]

From Sandy Haven drive back to Herbrandston and around the head of Sandy Haven Pill to St Ishmaels. There is a small car park and toilets [SM 839072] adjacent to the sports field on the east side of the village. Lindsway Bay is a beautiful, quiet and little-known bay, despite the fact that it lies within 2km of the LNG terminal at South Hook. You should follow the footpath that leads from the car park to the coast path, then turn left and take the coastal track *c.* 200m to the steep steps that lead down to the beach in Lindsway Bay (Fig. 19). Care should be taken when

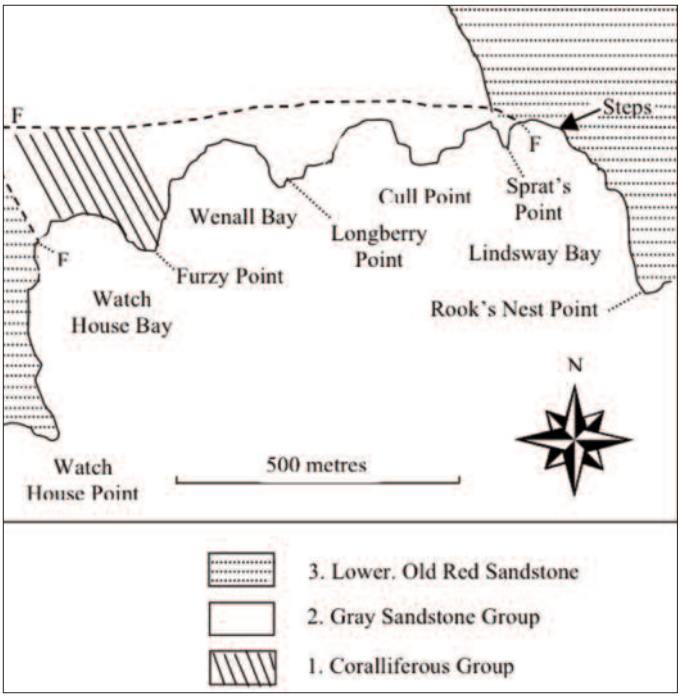


Figure 19 The geology of the coast between Watch House Point and Lindsway Bay.

descending the steps, as there are no safety rails. Walk across the beach to Sprat's Point on the west side of the bay, where the alternating sandstones and mudstones of the Gray Sandstone Group can be seen dipping *c*. 70º SW (Fig. 20). These beds pass conformably upwards into the basal Old Red Sandstone marls (Red Cliff Formation) on the north-east side of Sprat's Point, where the faulted junction is marked by a steep gully.

The Silurian rocks in Lindsway Bay form the most easterly exposure of the fault-bounded Marloes inlier. They also form the cliffs along the coast to the west, as far as Watch House Bay, but it is difficult to access the foreshore without using a boat. Even so, it is well worth walking along the coast path to observe the cliff structures from above. Longberry Point can be easily recognised by its massive sandstone beds that dip inland at a high angle. Furzy Point and Watch House Bay are formed of calcareous mudstones belonging to the Coralliferous Series that are folded into a major anticline, the axis of which runs roughly N–S through Furzy Point.

Figure 20 Gray Sandstone Group (Upper Silurian) at Sprat's Point, Lindsway Bay.

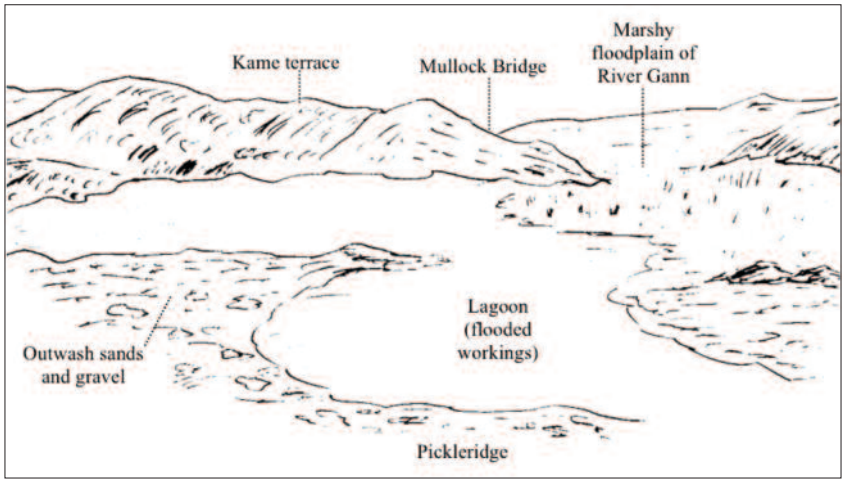


Figure 21 View looking northward to the Mullock Bridge Kame Terrace.

10. Mullock Bridge [SM 811080] & Townsend [SN 812060]

This locality is on the B4327 *c*. 3km west of St Ishmaels. It is of considerable geomorphological interest, as it provides a magnificent example of a kame terrace on the western side of the Gann estuary. This feature is a flat-topped mound of fluvioglacial sand and gravel that was deposited by meltwater at the junction of the wasting Irish Sea ice front and the valley side. The drift sequence, which was exposed in a large gravel pit *c*. 400m south of Mullock Bridge, was recorded in detail by Gareth George in the early 1970s. Unfortunately the pit has since been infilled and landscaped and is now entirely overgrown. However, the topography of the kame terrace can be appreciated by viewing it from the south in the vicinity of Pickleridge, where there is a car park [SM 809067] (Fig. 21).

Walk along the shingle ridge past the flooded pits that are now lagoons supporting a variety of wild life. In the banks of the lagoons there are exposures of fluvioglacial outwash sands and gravel. Pickleridge is a shingle ridge that has developed in a north-westerly direction along the high-water mark across the Gann estuary. This shingle barrier impedes the drainage on the marshy flood plain of Afon Gann that is inundated by the sea when there are spring tides. You will notice that there is a strong contrast in the natural vegetation between the dense colonies of reed mace (bullrushes) on the wet flood-plain of Afon Gann and the abundance of gorse and Scots pine that cover the dry sandy slopes of the kame terrace.

Continue along the road to Dale village where there is a car park alongside the beach [SM 811058]. Walk back along the road to the small group of houses at Townsend and descend to the foreshore near Black Rock. The Sandy Haven Formation forms the rocky foreshore here and it consists of alternations of thick vein quartz conglomerates, medium grained sandstones and red mudstones with calcretes. Immediately south of Black Rock the Townsend Tuff Bed can be seen cutting across the foreshore and following the strike of the sandstones (Fig. 22). The tuff outcrop is *c*. 4m thick and consists of three fining-upwards, graded air-fall units. The light coloured porcellanite (silicified dust tuff) contrasts with the darker, magenta-coloured, medium-grained, crystal-lithic tuff (crystal debris and rock fragments) at the base of each fall. Townsend is by far the most accessible place where you can examine the tuff bed in south-west Wales, and it is of course, named after this locality.

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Figure 22 Townsend Tuff Bed on the foreshore near Black Rock.

Book review

Schmidt, Anja , Fristad, Kirsten E and, Elkins-Tanton, Linda T. 2015 *Volcanism and Global Environmental Change*. Cambridge University Press (ISBN 978-1-10705-837-8; hardback, 324pp; £75)

Volcanic eruptions have the potential to produce profound global environmental effects, yet ascertaining the nature, magnitude and timescale of these events from the geological record has proved challenging. Volcanism and Global Environmental Change brings together European, Russian and US geologists, volcanologists, climate and atmospheric scientists and palaeobiologists to provide an invaluable update on the state of knowledge in this complex but intriguing area.

The volume is divided into three parts: Part One explores large-volume volcanism, including origins, features and duration; Part Two covers the assessment of gas and tephra release in the present-day and geological record; Part Three considers modes of volcanically-induced global environmental change. As each 'chapter' is the work of one or more different authors, the volume is inevitably more akin to a collection of papers than to a textbook.

Part One explores the potential for global environmental change produced by large igneous provinces (LIPs) and considers LIPs' connection with mantle-core dynamics and deep mantle plumes. So-called 'super eruptions' and their potentially catastrophic environmental consequences are also examined.

Part Two describes the increasingly sophisticated methods of monitoring current emissions. It further considers the role of volcanic emissions in the Permian-Triassic extinction, including the release of volatiles in LIPs, which may not only affect climate but also cause stratospheric ozone destruction, which is potentially harmful to life. Evidence of violent and surprisingly rapid release of sulfur-, carbon- and halogen-rich gases from sedimentary country rocks during contact metamorphism is discussed. In Siberia, for example, pipe structures with explosion craters exceeding 1km diameter suggest rapid mobilisation of large volumes of carbon and sulfur from sediments following the emplacement of sills and dykes. Contact metamorphism of organic material in offshore Norway might have been a cause of environmental change during the Paleocene-Eocene Thermal Maximum (PETM).

Part Three includes a review of modes of volcanically-induced environmental change, including halogen release and ozone depletion resulting from Plinian eruptions, volcanic ash deposition, Permian-Triassic ocean anoxia and ocean acidification. It concludes with a chapter on the environmental effects of LIP magmatism from the Siberian perspective that highlights the many challenges that remain for modelling volcanism.

Each chapter is comprehensively referenced, making the volume an excellent source for further reading. Unfortunately, the clarity of some colour figures is compromised by the small size of reproduction. Notwithstanding this, *Volcanism and Global Environmental Change* provides in a single volume a highly readable selection of recent material from scientists working in this important and fascinating field.

— Caroline Peters, BSc Hons (Open) Geoscience

OUGS crystallography and mineralogy workshop (Aberystwyth, 30–31 January 2015)

led by Charlie Bendall and Bill Perkins

text and diagrams by Elizabeth Edmundson

[This article was originally published in the Severnside Branch Newsletter, Sabrina Times, in May 2015. It is hoped that this slightly edited version will prove useful to members. —Ed.]

Introduction

If you find the very notion of crystallography, with all those axes, angles and planes of symmetry to be daunting, then this workshop was the answer. We used the Aberystwyth Park Hotel's conference room, which although lacking the facilities and specimens of the university lab, made hearing and seeing our instructors much easier. Bill and Charlie brought all the necessary kit, and we had excellent instruction.

On January 30 we were introduced to crystal structure, form and symmetry. By the end of the day, we were discussing various minerals and their crystal forms. We had a guest lecturer in the early evening — Prof. Nick Pearce, ably assisted by Amy (his daughter) and Jack (his son). He spoke on the latest diagnostic techniques for determining the sources of lavas from major eruptions. Prehistoric stone tools can also be dated using far less destructive methods; and how they fit in the archaeological sequences can tell us about the impact of such eruptions on human evolution.

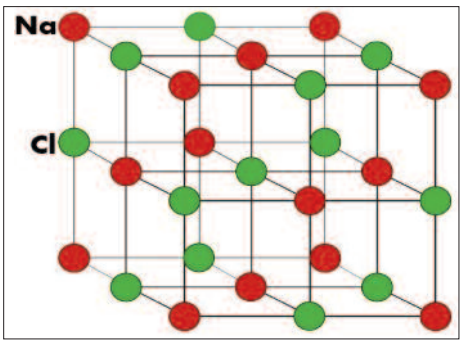
January 31 was dedicated to using the petrological microscope — how it works and how to interpret what can be seen in thin sections.

Basic definitions

We began with some basic definitions. Not all minerals are crystals. A mineral can be defined as a naturally occurring inorganic substance having a regular characteristic chemical composition and crystalline molecular structure. A crystal is a solid bound by a series of plane faces. A piece of quartz with six sides and a point at one or both ends is a crystal. A rounded sand grain of quartz would not be called a crystal, although its internal structure may be that of crystalline quartz.

Unit cells are the basic building blocks of crystals (Fig. 1). You may notice that the unit cell in Figure 1 is not so much NaCl as $Na_{14}Cl_{13}$. However, each atom on each face of the unit cell can share with one or more adjoining unit cells. The central atom on a face can share between two cells, the centre atoms on the edges can share between four, and the corner atoms can share between eight (Fig. 2). Consequently, by the time you get to $Na_{trillion}Cl_{trillion\&1}$ it does work within the lattice; besides, the odd ion does not matter that much!

Figure 1 A unit cell of halite — NaCl.



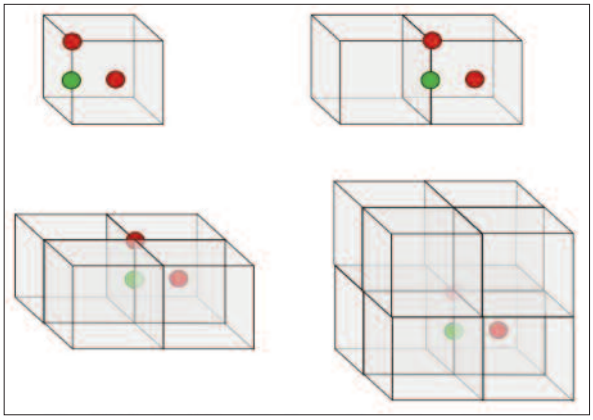


Figure 2 The building blocks and how they stack.

There are several rules governing unit cells:

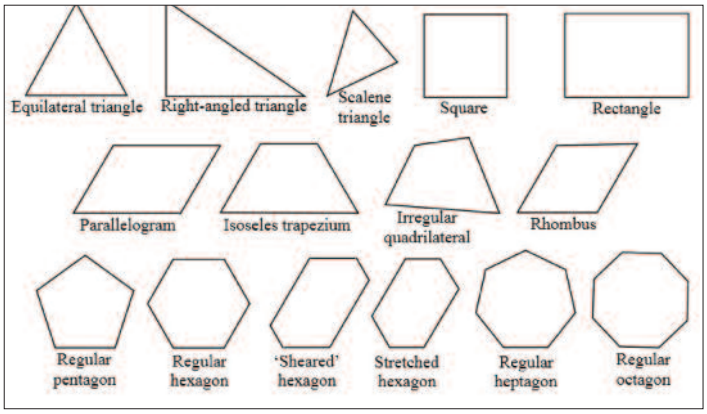
- ❒ Each must be the same shape and size.
- ❒ Each contains atoms in proportion and can share atoms in faces.
- ❒ Edges are straight lines.
- ❒ Each shares atomic relationship.
- ❒ Lattices are formed by stacks of unit cells.
- ❒ There are no gaps between unit cells.
- ❒ Unit cells can join by equal translation of all lattice points without rotation.

From these criteria we can to determine what shapes fulfil these rules.

To build unit cells into lattices, it is best to start at the beginning; with two-dimensional shapes (Fig. 3). What we are looking for are shapes that:

- ❒ are the same;
- ❒ can fit together along all their edges, and join points;
- ❒ have no gaps in the lattice;
- ❒ and have not been rotated.

Figure 3 2D strsaight-edged shapes.



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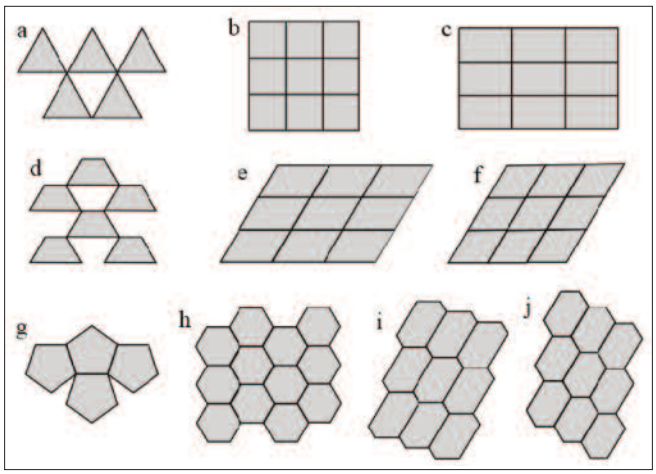
In Figure 4 we see that the square (b), the rectangle (c), the parallelogram (e), the rhombus (f) and the hexagons (h, i and j) all form 2D lattices without gaps. The pentagon (g), the heptagon and the octagon cannot join without gaps. The equilateral triangle (a), the right-angle triangle and the trapezoid (d) cannot join without 180° rotations, which would invert the molecular structure. So unit cell shapes must have:

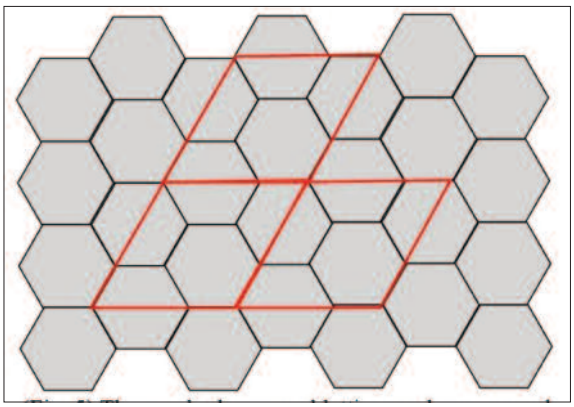
- ❒ an equal number of sides;
- ❒ opposite sides parallel;
- ❒ and internal angles divisible by 360°.

Figure 4 Fitting 2D chapes into lattices of unit cells.



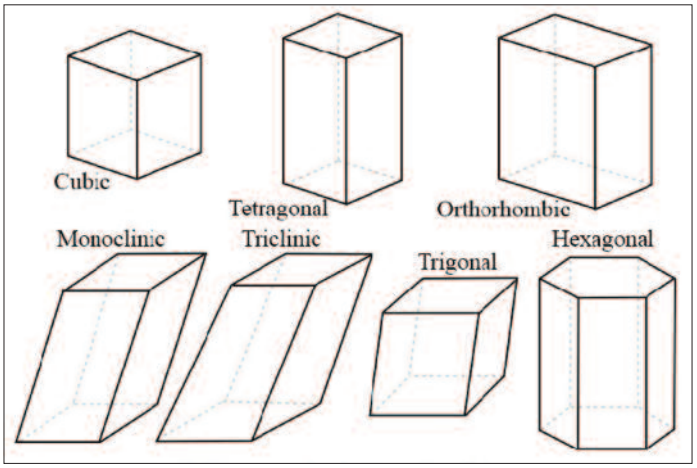
Regular polygons can be distorted provided opposite sides remain parallel and opposite angles are equal. Further, a rhomboid lattice can overlay a hexagonal lattice (Fig. 5), showing the same internal structure in each rhombus. Squares and rectangles do not work on the hexagonal lattice, because the internal structures do not repeat in each unit. The parallelogram does not work unless it is the length of two rhombi — in which case it is two rhombi, not a parallelogram. This restricts the number of basic 2D unit cell shapes to the square, the rectangle, the parallelogram and the rhombus.

Figure 5 The regular hexagonal lattice can be expressed as a rhomboid latitce.



However, crystals are three-dimensional: 3D unit cells are extensions of their 2D counterparts and obey the same rules regarding opposite faces parallel, opposite internal angles equal, straight lines, no rotation, etc. The four basic 2D shapes extend into seven basic 3D shapes: cubic (isometric), tetragonal, orthorhombic, monoclinic, triclinic, trigonal and hexagonal (Fig. 6). Cubic is the extension of the square; tetragonal and orthorhombic are extensions of the rectangle; monoclinic (skewed orthorhombus) and triclinic (orthorhombus skewed more than once) are extensions of the parallelogram; and trigonal and hexagonal are extensions of the rhombus.

Figure 6 The seven basic 3D unit shapes.



3D symmetry

We spent the afternoon coming to terms with 3D symmetry — axes and mirror planes. After dividing a few 2D shapes into equal parts through their centres (Fig. 7), we started on the seven 3D unit cells. One of the elements of symmetry is axial symmetry, which involves putting an axis through the central points of opposing faces or edges, or through opposing corners. The rotation around any axis must present the same aspect to be counted as so many '-fold'. For example, a cube (Fig. 8) has six faces, eight corners and 12 edges. If you cut a cube of cheese, put a toothpick through the opposing faces and turn it around, the same view of it happens four times — you can do this three different times before you run out of punctured faces, so a cube has three

Figure 7 Rotational symmetry.

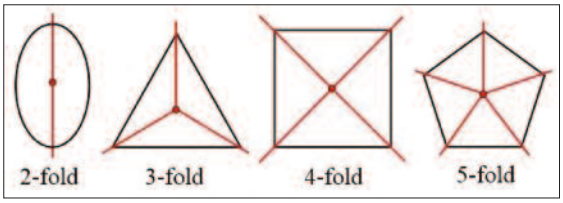
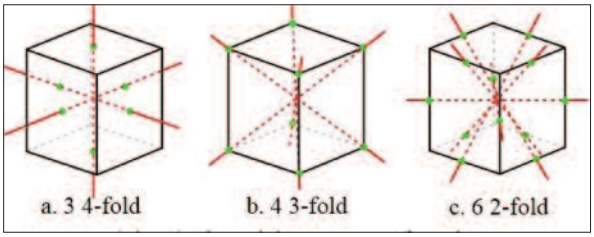


Figure 8 The axial symmetry of a cube.



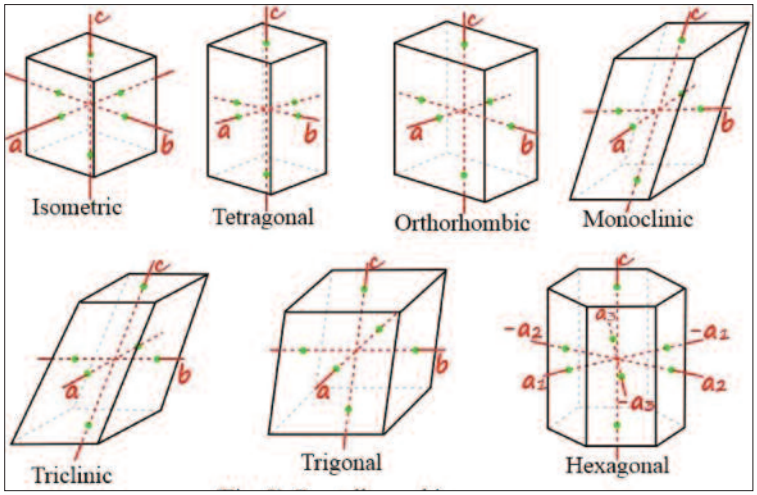


Figure 9 Chrystallographic axes.

four-fold axes through its faces. If the toothpick is corner to corner, you can do this four times; turning it gives the same view three times — four three-fold axes. Edge-to-edge can be done six times, but the view is the same only twice — six two-fold axes.

Crystallographic axes intersect the centres of the faces of the basic shapes (Fig. 9). By convention, the vertical axis is *c* in Figure 9. The two axes horizontal to ***c***, are ***b*** and ***a***. In the case of hexagonal crystals, there are three horizontal axes, $\boldsymbol{a_1}$, $\boldsymbol{a_2}$ and $\boldsymbol{a_3}$. Lengths of axes relative to each other, as well as the angles between axes define shape:

- ❒ isometric: lengths $\boldsymbol{a = b = c}$; angles $\boldsymbol{ca = cb = ab} = 90°$ — includes halite, garnet, fluorite, pyrite, galena and magnetite, as well as diamond, gold and several other elemental minerals.
- ❒ tetragonal: lengths $\boldsymbol{a = b \neq c}$; angles $\boldsymbol{ca = cb = ab} = 90°$ — includes zircon, cassiterite, rutile, wulfenite and chalcopyrite.
- ❒ orthorhombic: lengths $\boldsymbol{a \neq b \neq c}$; angles $\boldsymbol{ca = cb = ab} = 90°$ — includes olivine, barite, sulfur, topaz, staurolite, andalusite and the pyroxene enstatite.
- ❒ monoclinic: lengths $\boldsymbol{a \neq b \neq c}$; angles $\boldsymbol{ca = cb} = 90°$, $\boldsymbol{ab} \neq 90°$— includes the feldspar orthoclase, amphibole, epidote, gypsum, azurite, malachite and the pyroxenes diopside and augite. Sugar (sucrose) also forms monoclinic crystals.
- ❒ triclinic: lengths $\boldsymbol{a \neq b \neq c}$; angles $\boldsymbol{ca \neq cb \neq ab} \neq 90°$ — includes the feldspars plagioclase and microcline, rhodonite and axinite.
- ❒ trigonal: lengths $\boldsymbol{a = b = c}$; angles $\boldsymbol{ca = cb} = 90°$, $\boldsymbol{ab} \neq 90°$ — includes calcite, dolomite and tourmaline (hexagonal ditrigonal).
- ❒ hexagonal: lengths $\boldsymbol{a_1 = a_2 = a_3}$; angles $\boldsymbol{a_1a_2 = a_2a_3 = a_1a_3} = 120°$, $\boldsymbol{ca_{1,2or3}} = 90°$ — includes quartz, apatite, beryl (emerald, aquamarine), corundum (ruby, sapphire) and arsenic.

We had a brief discussion on mirror planes. Imagine a mirror intersecting a cube in a plane of two of its axes. If the reflection looks like the whole cube, then that plane is a mirror plane. We also looked at zones — areas of a crystal shared by parallel edges.

A major factor in a crystal shape will be its chemical composition. Halite and garnet are both isometric, but the molecular lattice of halite (NaCl) is far less complex than that of garnet ($Fe_3Al_2Si_3O_{12}$), so halite crystallises as a cube, while garnet grows a few extra faces.

Of course, real mineral crystals are not all basically shaped — axes can intersect just about anywhere on faces, edges and corners. So, Charlie and Bill introduced us to 'Miller indices', which define crystal faces, points and/or edges as the axes intersect them. If a face cuts three axes, then the distances from the centre on the axes — e.g. $\boldsymbol{a} = 2$ units, $\boldsymbol{b} = 2$ units, $\boldsymbol{c} = 1$ unit — are converted to their reciprocals — ½, ½, 1; then these are multiplied by the lowest integer. In this example 2 — to give lowest integers. This would give indices of **1 1 2**.

Where a face intersects only one axis, the default unit is 1 and the other two axes, which never intersect the same face, are given the value ∞ (infinity). Their reciprocals are **1/1 (=1)**, **1**/∞ (which pretty much equals 0) and **1**/∞ (**0** again). So if it is the ***a*** axis intersected, then the Miller indices are **1 0 0**. As a matter of interest, a hexagonal crystal gets four Millers!

Miller indices take some getting used to. A glance at such a set of figures conveys plenty of information as to the variations on basic shapes to a practised eye. It is amazing that Bill and Charlie managed to get across as much as they did on this point in about half an hour!

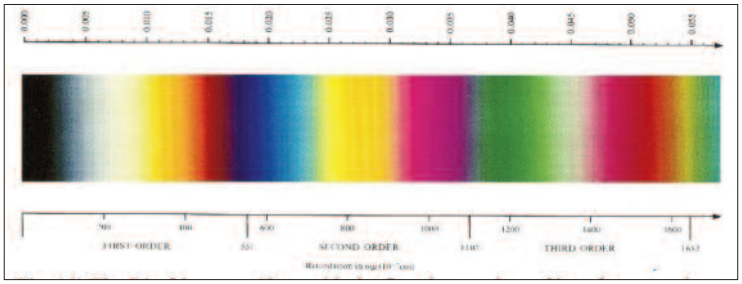
All of these factors — shapes, axes, angles, mirror planes, zones and Miller indices — are diagnostics for mineral identification, along with colour, lustre, hardness, etc.

Thin section day

We began by familiarising ourselves with the polarising microscopes: how to work them, which knobs do what, and what *not* to twiddle. We then went through a few definitions:

- ❒ polarised light: light waves made to vibrate along one plane. In the microscope, a single polarising lens is the 'plane polarised light' setting, and is below the thin section.
- ❒ crossed polars: a polarising lens set above the thin section. The upper lens can be rotated in relation to the lower lens. If two planes of polarised light are at right angles to each other, non-refracted light blacks out, while refracted light shows in a range of intensities and colours.
- ❒ refraction: the change in deflection of light passing from one medium to another. The refractive index is the ratio of $\boldsymbol{V_1}$ over $\boldsymbol{V_2}$, with $\boldsymbol{V}$ = the speed of light and $\boldsymbol{_1}$ and $\boldsymbol{_2}$ = the speed of light through medium 1 and medium 2.
- ❒ birefringence: the difference between refractive indices. In thin section under crossed polars, it shows as interference colours (Fig. 10).

Figure 10 The Birefringence Chart with the first three orders of interfernece colours.



- ❒ interference colours (under crossed polars): caused by polarised light splitting and travelling at different velocities as it comes up through the crystal, then recombining through the upper polarising lens. Generally, if the light is out of phase by a wavelength, you get 'first-order colours'; two wavelengths get 'second-order colours'; three wavelengths, 'third-order'.
- ❒ extinction (under crossed polars): the point at which the light coming through the crystal blacks out. Extinction occurs at every 90° (the cross hairs in the field of view). Extinction of a crystal aligning with the cross hairs is 'parallel' (or 'straight'); extinction at an angle to the cross hairs is 'inclined' (or 'oblique').

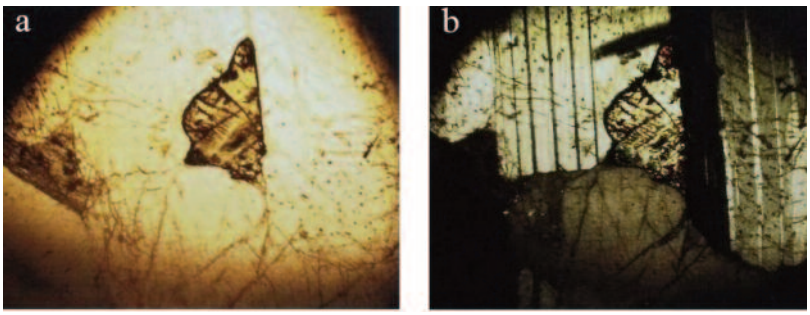


Figure 11 (a) A thin section under plane polarised light, showing the difference between high and low relief; (b) under cross polars, the featureless areas either side of the crystal show the 'pyjama stripes' of palgioclase (photos by E. Edmundson).

We began by viewing thin sections by eye. You can see how the sample is structured, grain size and some colour. Under the microscope, using plane polarised light (***ppl***) you can see several diagnostic features:

- ❒ colour: Most show no colour, but some do; e.g. amphibole (green or brown), biotite (brown) and garnet (pale pink).
- ❒ pleochroism: a wavy effect in a crystal as the stage is turned.
- ❒ relief: how well the mineral shows its shape. Minerals with higher refractive indices tend to have higher relief.
- ❒ shape: often the crystals show their growth shapes.
- ❒ cleavage: If a mineral has cleavage planes, these often show up in thin section. Some minerals have characteristic cracks and fractures.

Under crossed polars (**xp**), shapes and cleavages of low relief crystals become visible, plus:

- ❒ interference colours: it is difficult to resist the visual impact of the interference colours. Those peacock blues, golden yellows, flaming magentas, emerald greens and striking black and white patterns are actually good diagnostic indicators. Crystals that stay black at any position of the stage are isotropic, and are inevitably isometric.
- ❒ extinction: relates to cleavage. Quartz, which has no cleavage, shows wavy extinction.
- ❒ twinning: some minerals grow distinct twins, which show up well under ***xp***. Occasionally, twinning can be seen under ***ppl***, but is usually quite faint.
- ❒ alteration: shows up as a mishmash of 'dirt' around the crystal, indicating breakdown of the crystalline structure.

The rest of thin section day was spent viewing minerals within rocks in thin section. Figures 11, 12 and 13 show some of the results. Some of the minerals we looked at were:

- ❒ quartz: under ***ppl*** there is little to see — no colour, no pleochroism, no cleavage, low relief and not much to show in shape, except where other minerals start. Under ***xp***, grains become very distinct, with first-order colours of white to grey to black (extinction). There is not much alteration, but grains can show undulose extinction, caused by strain.

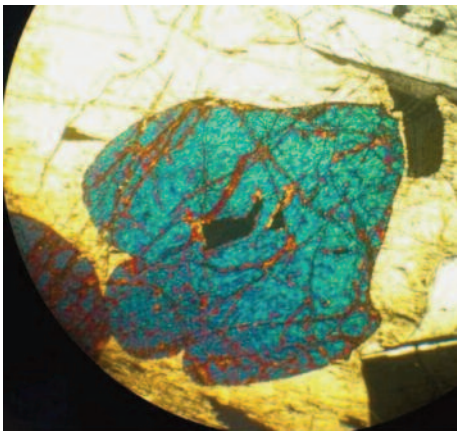
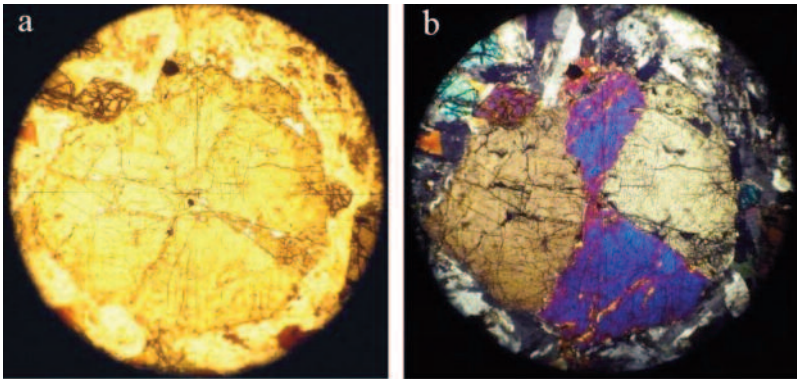


Figure 12 An olivine crystal under crossed polars (photo by Rebecca Pike).

- ❒ plagioclase: again, there is no colour or pleochroism under ***ppl***; and with low relief, shape and cleavage are only faint. Under ***xp*** — shapes and cleavage show, with first-order greys and lamellar twinning — the characteristic 'pyjama stripes'.
- ❒ orthoclase: ***ppl*** — no colour or pleochroism, low relief, but some messiness (exsolution into clays), the alteration indicating elongated shapes with a few striations but no cleavage. Under ***xp*** — first-order greys, several simple twins, slight wavy extinction in some crystals.
- ❒ calcite (marble): ***ppl*** — colourless and no pleochroism; moderate relief; irregular shapes with definite cleavages running at *c.* 120° to each other. Under ***xp*** the interference colours are very high-order (for example, off the scale in Figure 10), appearing as a variety of dullish pastels. Lamellar twinning shows along cleavage lines.

Figure 13 Twinning in a clinopyroxene crystal under (a) polarised light and (b) crossed polars (photo by Linda Fowler).



- ❒ olivine: ***ppl*** — faint (almost no) colour, no pleochroism, high relief; shapes are fairly regular and usually criss-crossed with fractures (no cleavage). Under ***xp*** — different brilliant colours of the second-order; the fractures often show alteration products.
- ❒ biotite: ***ppl*** — browns, very pleochroic; high relief, tabular shape with lengthwise cleavage. Under ***xp*** — second-order colours tinted by brown.
- ❒ pyroxene (clino-): ***ppl*** — very pale brown, may show slight pleochroism; high relief, regular and irregular shapes, two cleavages at *c.* 90°. Under ***xp*** — strong first- to second-order colours (blues, yellows, rich browns, greys); twinning, when it happens, is simple.

We could have spent much longer viewing and picking out crystals in thin sections, but the weekend came to an end. There was a lot of information given to us during the two days and we all appreciated Charlie and Bill for explaining it all to us.

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OUGS Chairman Linda Fowler attended and has posted photos from the weekend on her ‘Rocks and Olives’ blog.

Confronting barriers to inclusion: opening the gate to accessible geological fieldwork

Diana Smith, BA, BSc (Hons)

Held on June 26, 2015, the meeting was organised by the Geological Society of London, Higher Education network and University Geosciences in the UK, and held in the Geological Society, Burlington House, Piccadilly, London.

Edmund Nickless (former Executive Secretary of the Geological Society) introduced the conference and posed three questions for consideration, as follows:

1. Does the emphasis on fieldwork in geoscience education discourage the participation of people with disabilities?
2. How can we design and deliver fieldwork that is inclusive and accessible for people with disabilities?
3. How can we ensure that geoscience education and professions attract and develop the talents of people with diverse abilities?

Alhough the questions appeared to focus on professional and higher education, speakers from schools, Further Education and organisations for both formal and informal geoscience education took part. The OUGS falls into this category.

The meeting discussed the perceived 'macho' image of fieldwork, which is critical to professional geological practice and the development of field skills, in the past seen to appeal, in the main, to young, male 'outdoor' types who can cope with a rigorous schedule of fieldwork. On the other hand, talented learners with disabilities can be deterred, because it makes both physical and physiological challenges that are too difficult for them to cope with. This discussion prompted consideration of geoethics: should we have a culture of disclosure (already we ask people if they have 'dietary requirements'; should we ask if they have 'other requirements' also?); and a consideration of the type of leadership we need to encourage ethical and inclusive behaviour — do we need 'enforcement' or 'encouragement'?

Keynote speaker: Chris Atchison (University of Cincinnati, and Director of the International Association for Geoscience Diversity) His work has involved developing a programme to "encourage the use of a wide spectrum of experiences in the field and lab to encourage retention" rather than use the previous 'rigorous', field-based instruction that discourages those with disabilities from active engagement.

Stressing 'positive disclosure', where learners explain what help they need, without the need to explain why, should be seen as of paramount importance. It is also important that the 'educators' should be aware of the learners' abilities, rather than their disabilities.

Once you have that knowledge, 'flexibility' is the great key. That emphasis must be coupled with the availability of adequate help in the field. The old adage 'many hands make light work' was quoted — personnel to act as an 'enablers' are crucial.

As Chris was speaking, I felt that this work was almost 'reinventing the wheel'. The OU has already done this, to great and successful outcome, in the work that our 'special needs' weeks at Summer School did for both 2nd- and 3rd-level courses!

Miguel Gomez-Heras (Instituto de Geociencias y Ciencia sin Barreras) told us about fieldwork they have been doing in southern Spain with deaf and sight-impaired people, using the turbidite successions. Miguel's presentation stressed the fact that such experience worked well, but needs two helpers for each participant. The enjoyment of the participants was evident in the presentation.

Angela Bentley (ESTA — Earth Science Teachers Association) and Aquinas College) presented three case studies from the school, all of which showed how important 'disclosure' was — in order that the necessary arrangements can be made for keeping students with mental health issues able to participate safely. A couple of the cases could easily have ended in disaster.

Alison Stokes (Plymouth University and Geological Society Higher Education Network) backed up the previous speakers and finished with the maxim that [paraphrasing] "anybody [who] gets into geosciences, regardless of age or limitations, must have the opportunity to learn and not be judged", which was based on what some of her students had said when given the opportunity to complete work at their own rate, rather than under stressed conditions.

Jacqueline Houghton (University of Leeds) and colleagues have been developing material for learning field skills in the virtual world. They use landscapes and outcrops specifically designed so that students can use these to get training in mapping skills before they venture out in the field. Technology has moved on since the OU first designed the 'virtual field trip', and this looks like a promising way forward. She stressed that such work was in no way a replacement for fieldwork, but that it was a technical aid to fieldwork.

Gary Nichols and **Wayne Gladwin** (Nautilus Ltd) looked at how planning and proper risk assessment was crucial in any field work situation. Their work was particularly targeting continuing professional development (CPD), and showed how important it was that the planning put the participant at the centre of the process, asking what learning outcomes did they expect, what limitations did they have (disclosure again, but done by detailed discussion), what extra support was needed, and what insurance needed to be in place to cover it all.

General session of discussion

Further discussion then ranged widely over the ideas presented above. It was decided that there should be a follow-up meeting later in the year. Discussion at the reception afterwards was most interesting and enabled me to make contact with participants from Cardiff, Swansea and Plymouth. It appears that we are trying to sing from the same hymn sheet.

The OUGS is already well placed to address these issues, but I feel that we need to contribute to future meetings and use the experience we have for the benefit of others.

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Claxheugh, Ford Quarry and Tunstall Hill, led by Dr Andy Lane (Trip 2 at the OUGS Newcastle Symposium 2015)

Averil Leaver

Our small group collected promptly to leave for the drive to a car park on the banks of the Weir, a few miles west of Sunderland, where we were to meet our leader. We had come to this area to examine the Lower Permian Yellow Sands and the Ford Formation reef facies and associated features.

As the clouds started to clear we walked down to the riverbank to look across the river to the unconformity. Here the Basal Permian Sands can be seen sitting on an uneven erosional surface of the Carboniferous Upper Coal Measures, nearly masked by purple staining due to deep weathering (Fig. 1). The riverbank still shows evidence of its industrial past, with the remains of a coal staithe, a lime kiln and, farther downriver, the abandoned concrete hulk of an experiment in shipbuilding.

Figure 1 The unconformity between the Permian and the Carboniferous on the bank of the River Weir at Claxheugh.

We turned back to look south at the mass of Claxheugh Rock (Fig. 2) and Dr Lane pointed out the deep recession at the top of the tree-covered, sloping foreground. This weakness is the marker of the Downhill Slide, a massive submarine landslip that removed the majority of the Raisby Formation, leaving thin segments of Marl Slate and the Lower Magnesium Limestone. The rock structure represents the seaward section of a reef, which built on top of the slide at the shelf edge of Zechstein Sea — the Ford Formation.

We walked up to the east end of the rock where a mass of Permian Yellow Sand is in contact with the Ford Formation. Those of us who managed the steep slope were rewarded with a close inspection of the slide surface within the recess and the cross-bedding of the Yellow Sand (Fig. 3, *overleaf*).

A short bus ride and walk took us to Ford Quarry, a disused Magnesium Limestone quarry that is now preserved as a Site of Special Scientific Interest (SSSI) because of its geology. It was surrounded by a protective fence! But we walked around the end of it and entered a delightful meadow studded with common orchids (Fig. 4, *overleaf*). The mass of the Ford Formation reef is evident, with some stratification on the top indicating that this was the top surface of the reef and that talus had been moved by the waves. Farther west down the quarry Dr Lane pointed out the back edge of the reef, where debris had fallen into the lagoon and formed further stratified backreef deposits (Fig. 5, *overleaf*). We did not look for any fossils in this locality as the high level of dolomitization would have destroyed any evidence. The short showers of rain did not dampen are enthusiasm as we were surrounded by some beautiful examples of the flora of this lime-rich environment (Fig. 6, *overleaf*).

Figure 2 Claxheugh Rocks, Upper Permian Ford Formation reef limestone sitting on the surface left by the Downhill Slide (marked by deep recession).

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Figure 3 Slide surface between the Ford Formation reef limestone and deeply recessed Permian Yellow Sand.

Figure 4 Ford Quarry enclosing grass and flower meadow: an SSSI.

Figure 5 Ford Quarry showing landward side of reef core (left) and stratified backreef deposits (right).

Figure 6 Common Orchid found in the meadow within Ford Quarry.

Next, we returned to the bus for the ride to Tunstall Hill. This is now a nature reserve, SSSI and the subject of a Geotrail walk leaflet produced by Limestone Landscapes, the subject of one of the afternoon talks by Tony Devos. A short walk past the allotments brought us to one of the 'Maiden's Paps' (named by homecoming sailors because of their shape). Here we were able to examine an exposure and found some bryozoans, crinoids and algal mats (Fig. 7), an indication that we were near the top of the reef.

We also had time to walk along the top of the hill to another quarry, to the side of an old railway track. Here our searches revealed a few similar fossils, including a branching sponge.

Back at the car park Andy thanked us for the interest we had shown and expressed his admiration of us as representatives of the OU. It had been his first encounter with the 'species'! We in our turn thanked him for an informative morning, which had not been blighted by the few short showers.

Figure 7 Tunstall Hill Reef, part of Ford Formation showing part of an algal mat.

Geology and the Great Tapestry of Scotland

Michael Perkins

I recently had the opportunity to visit the Great Tapestry of Scotland, which was being exhibited at Stirling Castle in February [2015]. The tapestry represents, in about 160 panels, the history (and prehistory) of Scotland, embroidered by a collaboration of hundreds of amateurs. The tapestry aims to cover not only the history of Scotland in terms of kings, queens and battles, but also represents cultural development and achievements. I had a good feeling that geology would be represented in this huge work, and indeed it is represented generously.

The panels are ordered chronologically, so the first, and largest panel we come across represents the geological history of Scotland (Figs 1 and 2). Though somewhat schematic, the major events we know and love are all present and correct: the formation and closure of Iapetus Ocean, the Caledonian Orogeny, Carboniferous and Palaeogene volcanism. All this is displayed in an extravagance of textures and colours, providing lots of fun attempting to unravel three billion years of geological history from a single two-dimensional design.

Geology takes a back seat for a while as we move through prehistory (including Scotland's first house at our favourite fossil locality, Barn's Ness), and the kings and queens era. All this is fascinating (each embroidered panel comes with a short description of the history being represented, with much of the history being unknown to me) but the geology doesn't start again until we reach

Figure 1 The geological beginnings of Scotland.

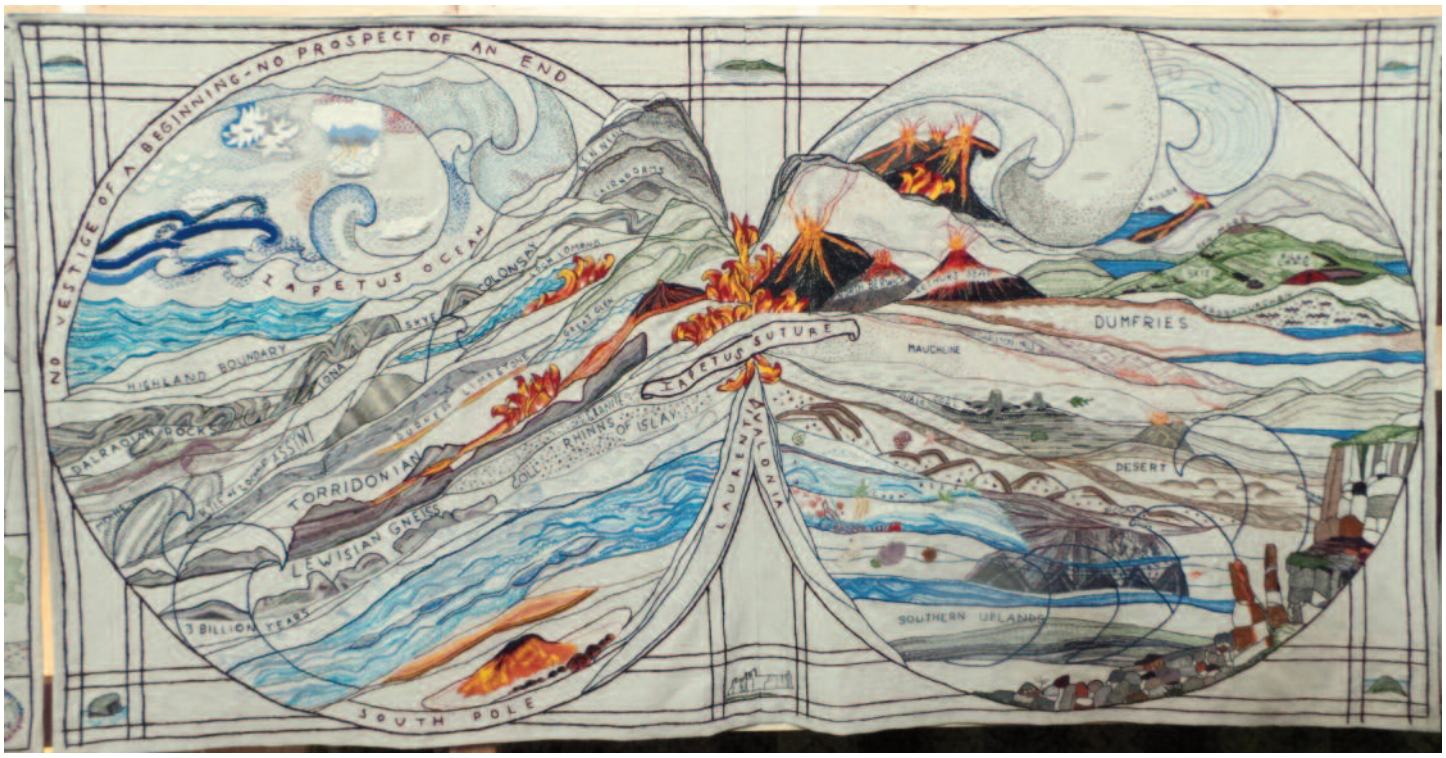

Figure 2 Detail of Carboniferous volcanism.

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the Scottish Enlightenment. James Hutton gets a well-deserved panel to himself (Fig. 3) with vignettes showing some of his favourite localities and fossils. The best of these shows Hutton, Playfair and Hall on their famous boat trip to Siccar Point (Fig. 4).

Figure 3 James Hutton's contribution to geology.

Some interesting geological localities appear in the tapestry, even when not being used for their geological significance. The biggest of these shows Fingal's Cave on Staffa, with its wonderful basalt columns (Fig. 5, *opposite*); and the Eildon Hills (including Rubers Law, visited by the East Scotland branch a few years ago with Brian Upton) appear in a panel devoted to the The False Alarm Threat of Napoleonic Invasion 1801; and Salisbury Crags on Arthur's Seat in Edinburgh, where Hutton found the junction between the igneous dolerite and the underlying sedimentary rock and used this to illustrate his ideas on how rocks formed by natural processes (Fig. 6, *opposite*). We also see Bow Fiddle Rock (Fig. 7), near Cullen.

Figure 7 Bow Fiddle Rock, near Cullen.

Figure 4 Hutton's trip to Siccar Point.

Cromarty stonemason, geologist and writer Hugh Miller makes two appearances in the tapestry (Fig. 8, *opposite*). The first of these is in the Pioneers of Photography panel, and then again in panel depicting famous Scottish personalities.

Finally, industrial geology is depicted too, in the form of the dawn of exploitation of North Sea oil (Fig. 9, *opposite*).

The tapestry is an awe-inspiring work, giving a highly engaging trip through Scottish history. But I am glad that, given that Scotland has had such a large part to play in the development of geology as a science, that it has not been forgotten. I would highly recommend to anyone who has not yet seen it to go and see the tapestry — perhaps you will find geological references that I have missed?

More details about the tapestry, including all the original panel designs, can be found at:
http://scotlandstapestry.com/index.php?s=tapestry.

Figure 5 Fingal's Cave on Staffa.

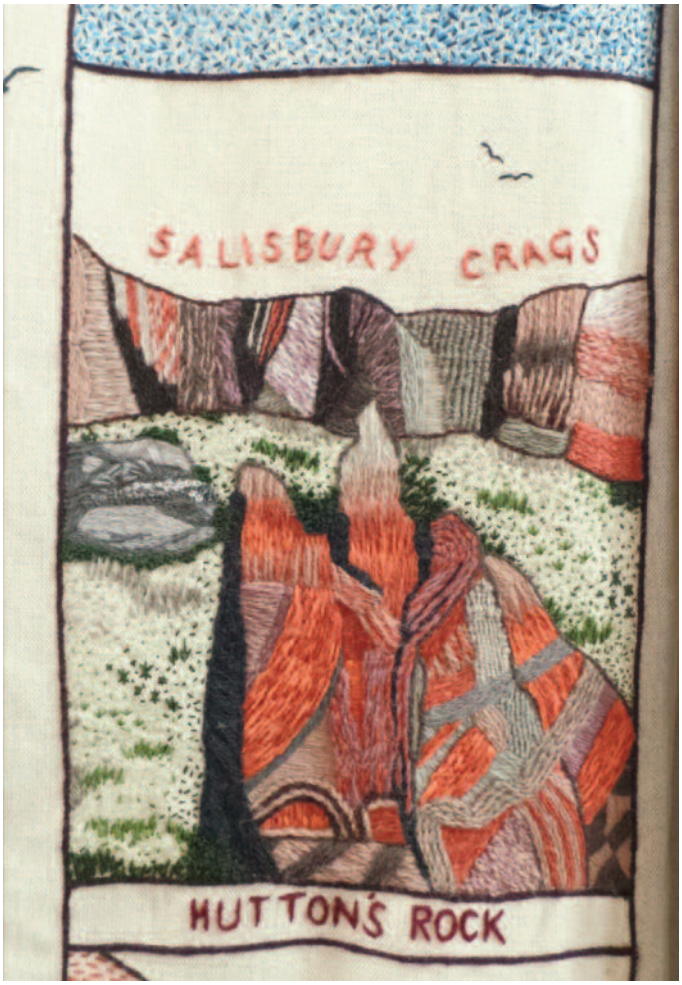
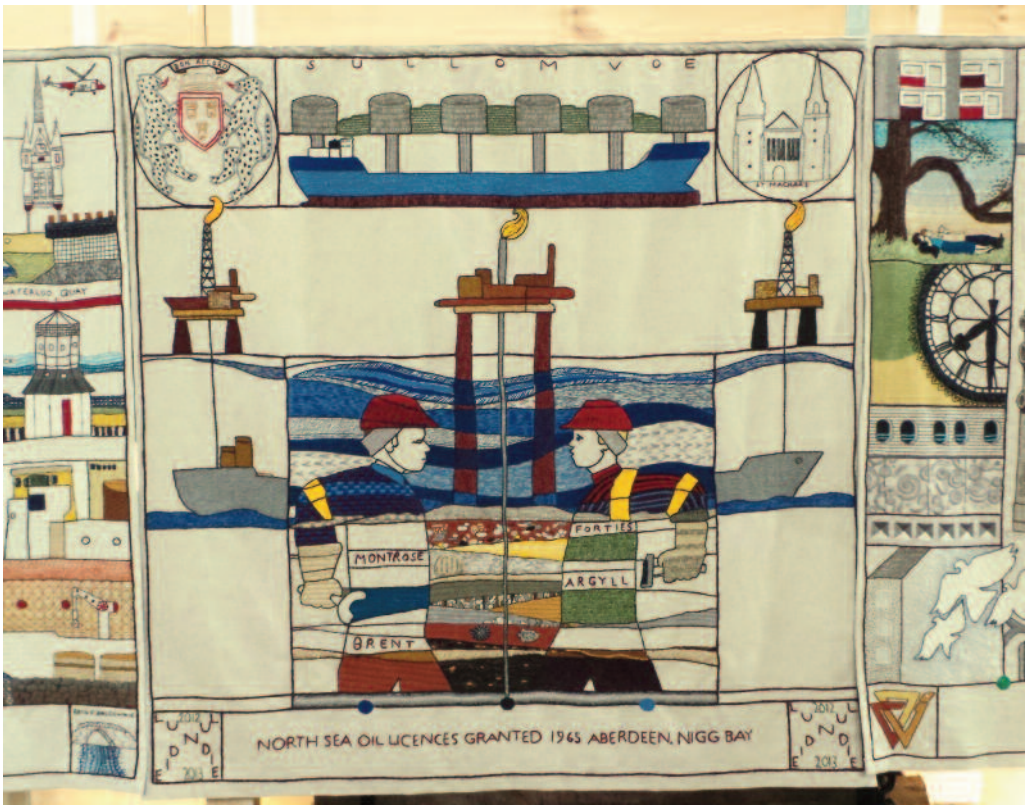


Figure 6 Salisbury Crags on Arthur's Seat — 'Hutton's Rock'.

Figure 8 Hugh Miller.

Figure 9 The dawn of exploitation of North Sea oil.



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Here are the basic guidelines. I will contact you about any queries that arise when I read your article. I will send you an edited version, showing you any changes that I have made and raising any queries or requesting any missing information.

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The Oxford English Dictionary

The Penguin Spelling Dictionary 1990. London: Penguin Books Ltd

Ritter, R. M. (ed and comp.) 2000 *The Oxford Dictionary for Writers and Editors* (2nd edn). Oxford: Oxford UP

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Please contact me at any time about your paper:

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OUGS Moyra Eldridge Photographic Competition 2015

Winning and Highly Commended photographs

Popular Vote, Winner — Linda McArdell; also Geological Feature or Structure Winner

Liesegang rings in the ferruginous sands of the Vectis Formation, Sandown Bay, I.O.W.

Geologically Inspired Landscape, Winner — Leon Angrave; also Popular Vote Highly Commended

Panorama of Alpine glaciers from Gornergrat, above Zermatt, Switzerland, with the iconic Matterhorn on the far right.

Geologically Inspired Landscape, Highly Commended

— Linda McArdell

Salt Pans, Maras, Valley of the Incas,
high in the Andes, Peru.

Geologically Inspired Landscape, Highly Commended — Anna Saich

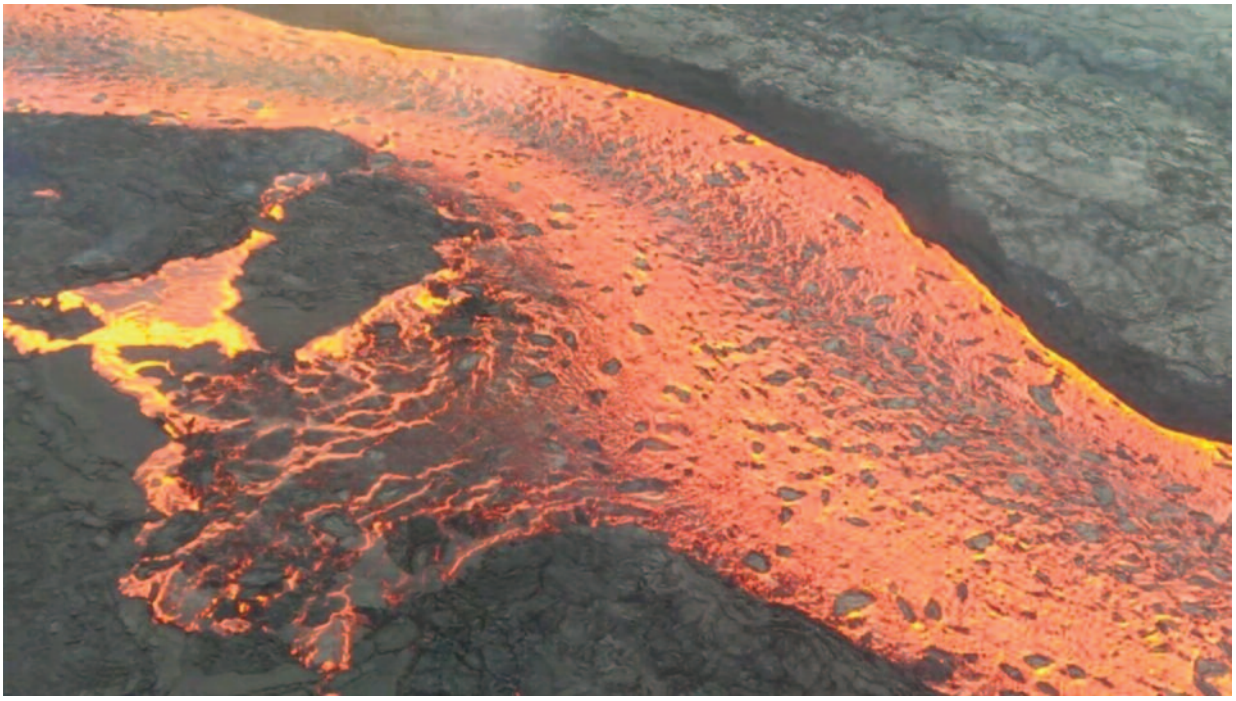
Sandstone Cliffs, Hastings. The cliffs to the east of Rock-a-Nore Road in Hastings Old Town are Lower Cretaceous rocks. Sandstones of the Ashdown Formation form the lower part of the cliffs, with the sandstones and shales of the Wadhurst Formation above.

Geologically Inspired Landscape, Highly Commended — Linda McArdell

Castle Rock, vertical Oligocene limestone in the Torlesse Range west of Christchurch, New Zealand.

Geological Feature or Structure, Winner — Linda McArdell

Liesegang rings in the ferruginous sands of the Vectis Formation, Sandown Bay, I.O.W.
[see Popular Vote, Winner]



Geological Feature or Structure, Highly Commended — Sarah Clark

Pahoehoe and lava rafts: a river of fast-flowing and very fluid lava issuing from a basaltic fissure eruption, showing formation of pahoehoe at a slower 'breakout'. Note the lava 'rafts' in the main course of the flow. Holuhraun, Iceland, September 2014.

Geological Feature or Structure, Highly Commended — Linda McArdell

Moeraki Boulders, Moeraki, New Zealand: the largest septarian nodules in the world.

Geological Feature or Structure, Highly Commended — Leon Angrave

Close up of fallen columns from the volcanic intrusion forming the Cascasas Los Tercios waterfall near Suchitoto, El Salvador.

Industrial Geology, Winner — Anna Saich

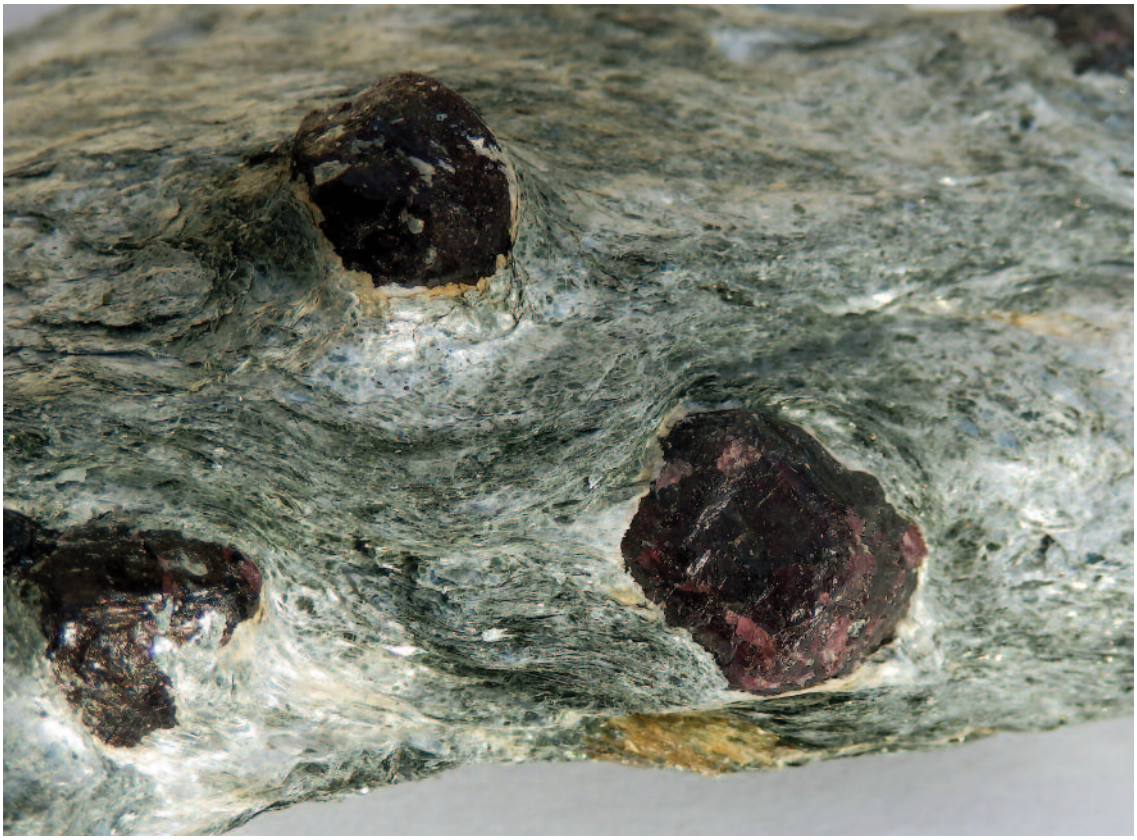
Marehill Sand Mines — local sandstones, including the Sandgate Formation seen at Marehill, were used in a number of the medieval churches around Pulborough.

Industrial Geology, Highly Commended — Linda McArdell

Salt Pans of Maras, Valley of the Incas, high in the Andes, Peru.

Mineral, Rock, Fossil or Slide, Winner — Linda McArdell

Siphonophyllia gigantia in Carboniferous Limestone, Ogmore on Sea, Glamorgan.



Mineral, Rock, Fossil or Slide, Highly Commended — Jenny Forrest

Garnet mica schist.

Mineral, Rock, Fossil or Slide, Highly Commended — James Jones
Quartz crystals.